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# SOILS OF HIGH-RAINFALL AREAS IN THE HAWAIIAN ISLANDS

BY

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By

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A PERMANENT SYSTEM of agriculture involves maintenance of soil productivity. This requires the preservation of the physical and chemical characteristics of the soil in such a state that the soil continues to be a satisfactory medium for the growth of crops.

Among the most important considerations in such maintenance are the base-exchange relationships of the soil. Study of these relationships extends beyond appraising the adequacy of supplies of the various exchangeable bases to meet the nutrient requirements of the crop. It includes determining the degree of acidity of the soil, which, within limits, is controlled by the exchangeable bases, and which in turn influences the microbiological activity of the soil and the availability of various substances. Further, the base-exchange relationships of the soil embrace the capacity of the soil to take up and retain added nutrient bases. They may include, as well, the effect of the exchangeable bases upon the efficiency of the sorption process.

Rainfall in the agricultural areas of the Hawaiian Islands covers the extremely wide range of from less than 20 inches to more than 200 inches annually. A generally open condition of the soil permits comparatively rapid penetration of water, so that even in areas of high rainfall there is little run-off except during the heavier storms. The soils in the more humid regions are therefore subject to intense leaching. Lysimeter studies of Magistad (28) show that leaching results in substantial losses of bases from Hawaiian soils. A factor which doubtless further intensifies the rate of leaching of bases in the humid areas is the extensive application of physiologically acid fertilizers.

If satisfactory crops are to be produced indefinitely under conditions of high rainfall, it would seem appropriate to inquire into such matters as the levels of exchangeable bases in the soils, the reserves of potentially exchangeable bases, the acidity of the soils (pH), the additional acidity that could develop from further depletion of the bases, the capacities of the soils to retain added bases, and the materials responsible for these capacities. Such knowledge of the chemical characteristics of the humid-region soils should aid in the determination of those agricultural practices that will insure continued productivity.

## PROPERTIES OF HAWAIIAN SOILS

The soils of the Hawaiian Islands have been formed from basaltic, and

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to some extent from andesitic, lavas and such derivatives as cinders and ash. An exception to this general rule is found in relatively small areas near the ocean, where the soils have been derived in greater or lesser degree from marine deposits, or reef rock.

The age of the surface layer varies from a few months, in regions of present volcanic activity, to many thousands of years, in regions where volcanic activity has long since ceased. This age factor has combined with the varied climatic conditions of the Islands to produce soils which differ widely in stage of development. In the young soils, differences in development associated with the physical nature of the parent rock are also apparent.

Silica, the principal acidic constituent of igneous rocks, is low in Hawaiian lavas, and quartz[1] is almost entirely lacking. These lavas are therefore considered to be basic in nature. Hawaiian lavas are likewise low in potassium. They are correspondingly high in iron and titanium, and in the bases, calcium and magnesium.

The agricultural soils of Hawaii are generally heavy in texture. Richter (50) concluded from his mechanical analyses that most Hawaiian soils may be classified either as clay loams or as clays. Subsequent studies of a number of soil profiles by Hough and Byers (18) and by Hough, Gile, and Foster (19) support this conclusion. Although Hawaiian soils contain large proportions of finely divided material, few, if any, possess full measure of those physical properties usually associated with the clay soils of temperate regions. This is particularly true of the residual soils which characterize the high-rainfall areas and which generally possess granular structures even when wet.

Early studies of the chemical properties of Hawaiian soils by Kelley, McGeorge, and Thompson (26) indicate that the soils are high in iron, aluminum, and titanium and relatively low in silica and the bases. Accordingly, these authors classified Hawaiian soils as lateritic soils. More recently, Hough and his associates (18, 19), in their studies of soil formation in Hawaii, also recognized laterization as the dominant type of weathering in the Islands. These workers obtained evidence also of podzolization in certain Hawaiian soils.

## DESCRIPTION OF THE SOILS EXAMINED

Although important agricultural areas on each of the principal islands of the Hawaiian group are situated in regions of moderately high rainfall, the present study has been limited for the most part to the soils of the Hilo and

[1] Although quartz is rarely found in Hawaiian lavas, the norms indicate that many of the lavas are potentially equivalents of quartz-bearing rocks (11).

Hamakua coasts[2] and of the Waiakea and Olaa plantations of the Island of Hawaii. The sugar plantations of the Hilo and Hamakua coasts comprise a belt of cane land several miles in width and extending for approximately 50 miles along the windward coast of the island. The cane fields, interrupted at irregular intervals by deep gulches, slope upward toward the interior of the island to elevations of more than 1,500 feet. The range in rainfall over this area is from about 65 inches annually, supplemented during certain seasons by irrigation, to a maximum of about 230 inches. This maximum is far in excess of the needs of the crop. Rainfall is generally heavier during the winter than during the summer months. The soils of Waiakea and Olaa plantations which are considered in this study are situated a few miles south of the humid end of the belt of plantations just described and do not border on the ocean. The fields are gently sloping. Rainfall in these areas is high. Along the windward coast of Hawaii, rainfall increases with elevation up to about the 2,500-foot level. Considerable differences in precipitation are, therefore, found between the lower and upper fields.

Prior to conversion of these lands to sugarcane production, the vegetative cover consisted of native forest, which was heavy in regions of high rainfall. Probably with few exceptions, the soils of these regions have been continuously planted to sugarcane since they were first brought under cultivation. Some of the lower- and middle-belt fields have been under cultivation for periods approximating 65 years; many of the upper fields were initially planted 25 or 30 years ago.

Studies by Smith (51) and by Wentworth (63) indicate that the sugarcane soils of the Hilo and Hamakua coasts have been derived principally from volcanic ash ejected from the neighboring volcano of Mauna Kea and laid down in varying depths upon older lava flows. Basic volcanic ash disintegrates rapidly under warm humid conditions, and these soils, although geologically young, are nevertheless highly weathered. They are generally deep.

The soils of Olaa and Waiakea plantations have been formed principally from *aa* lavas. These lavas are believed to have been derived from the still active volcano of Mauna Loa and possibly also to some extent from the active volcano of Kilauea. In relatively small areas untouched by the lavas (*kipuka's*) the soils are derived from older ash deposits. The Olaa and Waiakea soils which have lava as the parent material are younger geologically than the soils of the Hilo and Hamakua coasts (64). Owing to this fact and to the resistant qualities of the lava, as compared with ash, the lava-

[2] As employed in this paper, the term "Hilo and Hamakua coasts" includes the plantations from Paauhau Sugar Plantation Company to Hilo Sugar Company, inclusive.

derived Olaa and Waiakea soils are at an earlier stage of development than the Hilo and Hamakua coastal soils. They are shallow in many places and frequently stony. In this work only the lava-derived soils were sampled.

Although the present study centers about the soils just described, several samples were obtained from other areas. A few of these were taken from the humid cane- and pineapple-producing region of the Island of Kauai. These soils, believed to be among the oldest in the Islands, are highly laterized. The area was originally forested. Rainfall in this region does not attain the proportions of that encountered in some of the cane-producing areas of Hawaii. Several specimens of relatively old soils from the Island of Oahu were also obtained. The latter do not represent areas of high rainfall, and were selected primarily for contrast.

The Hilo and Hamakua coastal region offers an exceptional opportunity to determine the effect of rainfall upon some of the chemical properties of the soil. Not only is the precipitation range very great in this area, but a number of other factors important in soil formation are practically constant. Thus both the composition of the parent material and the age of the parent material are believed to be essentially the same throughout the area. Temperature differences are of a minor nature; the temperature decreases about 1° F. for each rise in elevation of 250 feet. Moreover, as has been mentioned, both the original and the cultivated vegetative covers have been practically uniform.

In the tables (inside back cover) the results pertaining to the soils of the Island of Hawaii are arranged in the order in which the soils are encountered as one moves southward along the coast from the less humid to the more humid regions. The wide differences in rainfall for a given locality result from the fact that samples were secured at different elevations.

## METHOD OF SAMPLING

Soil samples were obtained in the following manner. A short trench was dug, exposing the surface horizon and a foot or more of the subsoil. Ordinarily there is a sharp and distinct change in color between the surface layer and the subsoil; the depth at which this change occurs usually varies from about 6 to 10 inches, depending largely upon the elevation. Surface soil samples were taken of the upper horizon; subsoil samples were arbitrarily secured from the first 12 inches of the subsurface horizon. In a few instances, where no abrupt color change indicated a boundary between surface and subsoils, samples representing the depths from 0 to 6 and from 6 to 18 inches were obtained. The depths to which all samples were taken are indicated in the tables. The litter of dead plant material sometimes present on the surface of the soil was removed prior to sampling. Virgin soils were sampled in the same manner as the agricultural soils.

It should be pointed out that there is little evidence of a well-defined B horizon, or zone of illuviation, in Hawaiian soils. To the extent that this is true, surface and subsoil samples merely represent different zones within the A-horizon.

## METHODS OF ANALYSIS

### *Exchangeable Bases*

Exchangeable calcium, magnesium, and manganese were extracted from the soil with half-normal sodium acetate adjusted to pH 6.8. The soil sample was shaken with 250 milliliters of the replacing agent for an hour and the mixture allowed to stand overnight. The solution was then filtered off under suction, and an additional 250-milliliter portion of the replacing agent was allowed to percolate slowly through the soil.

Exchangeable potassium was extracted from the soil in the same manner as the other bases, except that normal ammonium acetate, adjusted to pH 6.8, was employed. Potassium in the extract was determined according to the method of Volk and Truog (60).

### *Total Bases*

Estimation of total bases was made by sodium-carbonate fusion. Frequently a 3-gram sample was necessary when the base content of the soil was very low.

### *Base-Exchange Capacities*

Base-exchange capacities were measured by the method of Parker (44). The reactions of the ammonium-saturated soils prepared during the procedure varied between the limits of pH 7.4 and pH 7.9.

### *Base-Exchange Capacities of the Mineral Fractions*

The soil organic matter was destroyed by heating at a temperature of approximately 300° C. for a period of 48 hours. Following this treatment, the exchange capacity of the organic-matter-free soil was determined. The work of Mitchell (41), Hovden, Wiklander, and Mattson (20), and others indicates that the base-exchange capacity of the organic matter can be destroyed in this manner without affecting the exchange capacity of the inorganic fraction of the soil.

### *Base-Exchange Capacities of the Soil Organic Matter*

The base-exchange capacities of the soil organic matter were obtained by subtracting the exchange capacities of the inorganic fractions from those of the whole soils.

*Determinations of pH*

Determinations of pH were made with the glass electrode. The soil-water ratio was not less than unity.

*Ultimate pH*

The pH of a soil after prolonged electrodialysis was considered the ultimate pH.

*Carbon*

Carbon was determined by the method of Walkley (62).

## EXCHANGEABLE CALCIUM

The acid nature of the humid-region soils was recognized before the beginning of the present century. During the years that followed this recognition, extensive liming operations were carried out by many of the sugar plantations. However, a large number of experiments with lime have failed to demonstrate a need for higher levels of calcium in the soil than were already present, as is indicated by the reports of Verret (58, 59). Moreover, as has been shown by Verret (59) and by Doty (15), adverse effects upon the quality of the crop have frequently resulted from liming. The practice, therefore, has gradually been abandoned.

Although the negative results obtained from the use of lime in Hawaii are in accord with experience in Mauritius (9, 54), they are at variance with results obtained in some other cane-producing areas. Turner (55), for example, has reported beneficial results in Trinidad from liming up to the lime requirement of the soil. A review by Turner of the effects of liming sugarcane soils indicates that favorable results from this practice have also been obtained in Australia, the Philippines, British Guiana, Cuba, and Java.

The level of exchangeable calcium necessary to meet the nutrient requirement of sugarcane has not been determined. Although the supplies of this base in all Hawaiian soils are presumably adequate to meet the need of sugarcane grown in the field, there have been instances in which response to calcium has been obtained with sugarcane in pots. Unlike Hawaii's two major crops—sugar and pineapples—some plants do not thrive in low-calcium soils. It has been the experience in this laboratory that acid soils must sometimes be limed before satisfactory growth of various plants will result. Magistad and Allen (30) obtained 300- to 400-per cent increases in yields of pigeonpeas in the field as a result of liming an Oahu soil containing about 0.7 milliequivalent of exchangeable calcium.

Sugarcane removes from the soil comparatively small amounts of calcium, considering the size of the crops grown. The extent to which the production of sugarcane depletes the soil of calcium depends upon the manner in which the crop is harvested, that is, upon the extent to which nonmillable parts of the crop are allowed to remain in the field. A 100-ton crop of cane removes from the soil about 100 pounds of CaO (3) exclusive of the calcium in the roots. Of this amount of calcium, only about 30 pounds are present in the millable cane.

The influence of rainfall upon the exchangeable calcium content of the soil has been studied by Craig and Halais (10) in Mauritius. These workers found that the level of calcium decreased with increasing precipitation throughout the rainfall range of 25 to 150 inches annually.

*Levels of Exchangeable Calcium*

The levels of exchangeable calcium in the cultivated soils examined are indicated in table 1. Considering first the Hilo and Hamakua coastal soils, it will be seen that the amounts of calcium present in the surface horizons cover a wide range, with an exceptionally low minimum. Thus the amounts of calcium vary from 0.2 milliequivalent per hundred grams of soil, or about 140 pounds of CaO per acre-foot, to 11.4 milliequivalents, or nearly 8,000 pounds of CaO per acre-foot. In the wetter regions the levels of calcium in the subsoils were substantially lower than in the corresponding surface soils, whereas in the drier districts this marked differentiation did not occur. The soils of Waiakea and Olaa contained amounts of exchangeable calcium that fall within the limits found for the soils of the Hilo and Hamakua coasts.

The remaining humid-region agricultural soils, those of the Island of Kauai, contained widely varying amounts of exchangeable calcium in the surface soils (1.87 to 13.5 milliequivalents). The subsoils contained smaller quantities of the base.

The wide fluctuations in the calcium content of the humid-region soils doubtless reflect, in part, the early liming operations in these areas, although, as will be seen presently, the rainfall is also a factor to be considered. The effect of liming is probably seen, too, in the fact that some of the humid-region soils contained larger amounts of exchangeable calcium than were found in the Aiea, Ewa, and Poamoho soils of Oahu, which are subject to the more moderate rainfall of 25 to 45 inches annually.

It is difficult to reconcile the low levels of exchangeable calcium in some of the soils studied with the lack of response of sugarcane to lime, particularly in view of the results which have been obtained in some agricultural regions. However, as far as the effect of lime upon the physical condition of the soil is concerned, there is little evidence that Hawaiian soils respond favorably to such treatment except possibly to amounts of lime in excess of those required to neutralize the soils. Moreover, as has been pointed out, the physical condition of these soils is generally good, and this is true even of soils which are practically devoid of exchangeable bases.

It has been suggested that this lack of response to liming is a result of the practice, in Hawaii, of allowing sugarcane to grow for periods approximating 24 months. Accordingly, the crop is allowed a longer period of time in which to absorb the necessary calcium than is permitted in some areas.

*Exchangeable Calcium in Relation to Rainfall*

The level of exchangeable calcium in the cultivated surface soils of the Hilo and Hamakua coasts appears to be correlated with the rainfall (see figure 1). It will be observed that the levels of exchangeable calcium decrease, although in a very irregular manner, with increasing rainfall. Undoubtedly, the irregularities are in some measure the result of early liming operations. In spite of the variations, however, statistical analysis of the data indicates a significant[3] negative regression between precipitation and exchangeable calcium. The levels of calcium in the subsoils were similarly found to decrease with increasing rainfall, and this relationship also was found to have statistical significance. These results are in accord with the observations of Craig and Halais (10).

[3] The use of the adjective "significant," or of equivalent terms in connection with the results of statistical analyses reported in this paper, implies a significance beyond the 0.01 level.

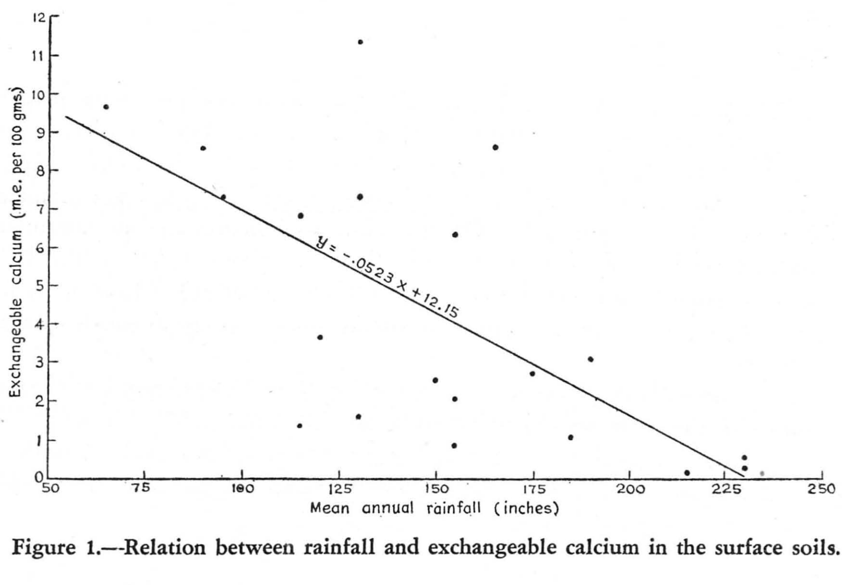


Figure 1.—Relation between rainfall and exchangeable calcium in the surface soils.

### *Effect of Agricultural Practices Upon Levels of Exchangeable Calcium*

Ascertainment of low levels of exchangeable calcium in some of the humid-region cultivated soils led to an attempt to determine whether the present status of these soils was attributable to the agricultural practices which have been imposed upon them. Accordingly, a number of samples of virgin soils were obtained from areas of fern and grass, and from forest, above the uppermost cane fields of several of the Hilo and Hamakua coastal plantations. These specimens were from locations comparable to those from which samples of cultivated soils were previously secured.

The data on the virgin soils and the adjacent cultivated soils are shown in table 2. Considering both surface and subsurface horizons, there appears to be no evidence that levels of exchangeable calcium are lower in the cultivated soils than in adjoining virgin soils. It would seem, therefore, that the low levels of the base in certain of the cultivated soils simply reflect the base-depleted condition of the virgin soils.

## TOTAL CALCIUM

It is sometimes worthwhile to inquire into the total amount of calcium present in the soil in order to determine the reserve of potentially exchangeable calcium. The matter merits more attention in the tropics, perhaps, where decomposition of primary minerals occurs at higher rates than in temperate climates.

Unweathered Hawaiian rock is unusually high in calcium, containing on the average 9 per cent CaO. The calcium minerals are rapidly decomposed, however, and many Hawaiian soils are very low in calcium.

### *Levels of Total Calcium*

The quantities of total calcium in the cultivated soils are shown in table 1. It will be seen from the table that some of the Hilo and Hamakua coastal soils contain very small quantities of total calcium. Thus, some of the surface soils in areas where the rainfall exceeds 100 inches contain as little as 0.15 per cent CaO. Other surface soils in this region contain up to 0.73 per cent. Several of the subsoils in the wetter regions of the Hilo and Hamakua coasts contain less than 0.10 per cent CaO. However, some subsoils, especially those in the less humid areas, contain as much as 0.40 per cent.

Exceptionally large reserves of calcium (2.24 to 3.24 per cent CaO) were found in the Olaa and Waiakea soils, and are presumably attributable to their early stage of development. The Kauai soils contained amounts of total calcium which fall within the limits found for this base in the Hilo and Hamakua coastal soils.

Although some of the humid-region soils have been depleted of nearly all of their calcium, such depletion is not wholly restricted to the humid areas. The Ewa and Aiea soils, for example, where rainfall is moderate, contained only 0.44 per cent CaO. Moreover, Magistad, Horner, and Dean (31) obtained values as low as 0.23 per cent CaO in Molokai pineapple soils, where rainfall was less than 20 inches annually. The latter value does not greatly exceed the lowest values found for calcium in the surface soils of the Hilo and Hamakua coasts. This similarity in levels of calcium is doubtless accounted for by the greater age of the Molokai soil. It appears to follow that, if sufficient time is allowed, depletion of calcium may proceed nearly as far under relatively dry conditions as under conditions of intense rainfall. This view is in harmony with that of Hough et al. (19).

### *Ratio of Exchangeable to Total Calcium*

The proportion of the total calcium present in exchangeable form may be taken as an indication of the degree to which the total calcium remains in insoluble or mineral form. It may also be taken as an indication of the degree to which the total calcium is immediately susceptible to leaching.

The proportions of exchangeable to total calcium in the soils examined are expressed, in tables I and 2, upon a percentage basis. There it will be seen that the percentage of total calcium present in exchangeable form ranges from as little as 2 to 57 per cent, in the case of the surface soils. In the subsoils the range is still wider, from less than 1 to more than 70 per cent.

The wide differences in the fractions of the total calcium present in exchangeable form appear to be related to the rainfall. This relationship, for the cultivated surface soils of the Hilo and Hamakua coasts, is shown in figure 2. Where the rainfall is least, the ratio of exchangeable to total calcium is highest, or somewhat over 50 per cent. As the rainfall increases, the ratio decreases until, at maximum rainfall, less than 5 per cent of the calcium is present in exchangeable form. This relationship was found to be statistically significant. A similar consideration of the distribution of calcium between exchangeable and mineral forms in the subsoils showed the relationship in this horizon also to have statistical significance.

## EXCHANGEABLE MAGNESIUM

The exchangeable-magnesium status of the humid-region soils merits closer attention, perhaps, at the present time than in times past. The cruder forms of potash fertilizers employed many years ago frequently contained appreciable quantities of magnesium salts. Small amounts of this base were thus regularly added to the soils incidental to the application of potash.

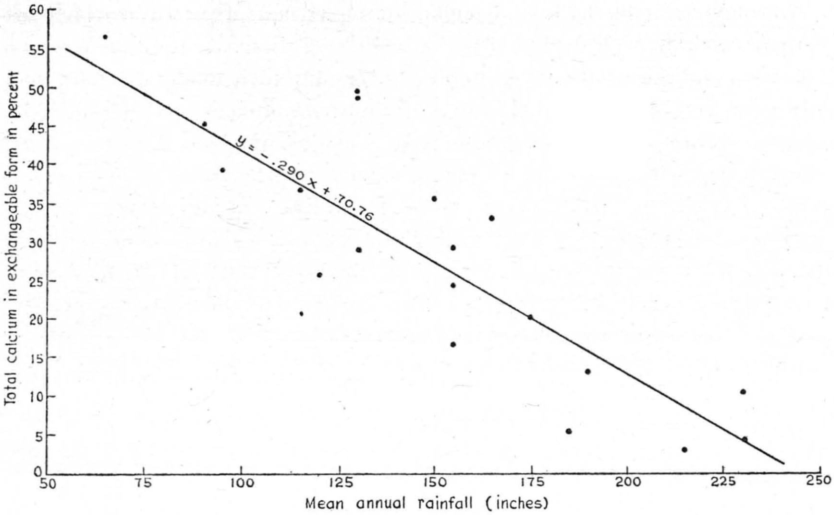


**Figure 2.—Effect of rainfall on the proportion of total calcium present in exchangeable form in surface soils.**

However, the concentrated forms of fertilizers currently in use in the Islands contain only negligible amounts of magnesium. It has been the experience in some other areas that changing from the cruder to the more refined fertilizers has brought to light unsuspected magnesium deficiencies.

Sugarcane has been found (3) to absorb from the soil in the neighborhood of 150 pounds of MgO per 100-ton crop, exclusive of the magnesium in the roots. Of the 150 pounds, approximately 70 pounds are present in the millable stalks. This is about twice the quantity of calcium present in an equal weight of stalks.

The level of exchangeable magnesium necessary to insure the normal growth of sugarcane has not been determined. Martin (34) has reported foliar symptoms of magnesium deficiency in field-grown cane in Hawaii. The supplies of exchangeable magnesium associated with the deficient plants, however, are not known.

### *Levels of Exchangeable Magnesium*

The quantities of exchangeable magnesium present in the cultivated soils studied are shown in table 1. The range of exchangeable magnesium in the surface soils of the humid regions is from about 0.3 to roughly 4.5 milliequivalents (150 to 2,250 pounds MgO per acre-foot of soil). More than one-third of these soils contain less than 1 milliequivalent of magnesium in the surface horizon. With a single exception the subsoils contain smaller amounts of exchangeable magnesium than the corresponding surface soils.

Exchangeable magnesium exists at considerably higher levels in the Oahu soils than in the humid-region soils. Values for magnesium in the Oahu soils range roughly between 5 and 10 milliequivalents.

With few exceptions, both surface soils and subsoils of the cultivated areas contained smaller amounts of exchangeable magnesium than of calcium. This is in accord with observations on most arable soils. Only where the amounts of calcium were extremely low, that is, a third of a milliequivalent or less, were the levels of calcium exceeded by the levels of magnesium.

*Exchangeable Magnesium in Relation to Rainfall*

The amount of exchangeable magnesium in the soil appears to be correlated with the rainfall. Evidence of this relationship is seen in the fact that the drier Oahu soils are better supplied with magnesium than the humid-district soils. The relationship may also be observed in the soils of the Hilo and Hamakua coasts. In figure 3, values for exchangeable magnesium in the cultivated soils of this region are plotted against the rainfall. It will be noted that the levels of magnesium are generally higher in areas

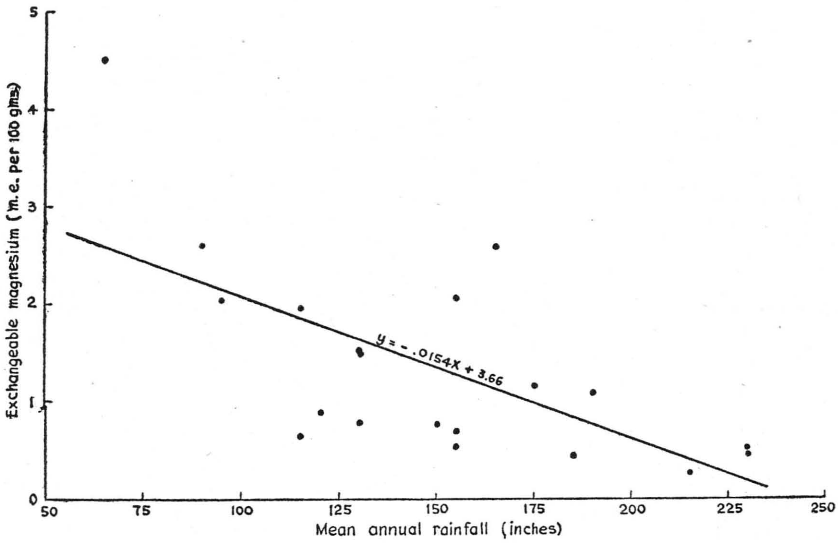


**Figure 3.—Relation between rainfall and exchangeable magnesium in the surface soils.**

of low rainfall, and that the values decrease with increasing precipitation. This relationship was found to have statistical significance.

The amounts of exchangeable magnesium in the corresponding subsoils of the Hilo and Hamakua coasts were likewise found to decrease with rainfall, but only up to a certain point. In this horizon the level of the base dropped from about 3.5 milliequivalents to a few tenths of a milliequivalent coincident with an increase in rainfall from 65 to about 115 inches. Above 115 inches of rainfall there was little consistent change in the level of magnesium.

### *Effect of Agricultural Practices Upon the Level of Exchangeable Magnesium*

The exchangeable-magnesium contents of the virgin and corresponding field soils are shown in table 2. Reference to the table will show that all of the virgin surface soils and three of the five virgin subsoils possessed larger quantities of this base than the corresponding cultivated soils. It appears from this comparison that the level of magnesium has been reduced as a result of the conversion of the land to the production of sugarcane. It is possible that to some extent this decrease may have resulted from erosion of the surface soil, which is higher in exchangeable magnesium.

The fact that the levels of exchangeable magnesium, though not of exchangeable calcium, have been lowered in these soils as a result of sugarcane production may be attributable to the following circumstances: First, more calcium than magnesium has doubtless been applied to the cultivated areas; and second, probably more magnesium than calcium has been removed by crops.

## TOTAL MAGNESIUM

As a rule Hawaiian lavas contain somewhat less magnesium than calcium. The reverse is the case in many local soils, however, where magnesium is frequently found at the higher level. Under some conditions at least, magnesium thus appears to be less susceptible to loss than calcium. This differential loss of bases is possibly attributable to the tendency of magnesium to form secondary minerals upon weathering, a property not possessed by calcium in acid soils.

### *Levels of Total Magnesium*

The surface soils of Kauai and most of those of the Hilo and Hamakua coasts contained levels of magnesium ranging from a little less than 0.6 to somewhat over 1 per cent MgO. The surface soils of Waiakea and Olaa and some of those near the southern end of the Hilo coast contained much higher levels of magnesium. Values as high as 9 per cent MgO were found in Olaa surface soils, testifying to the comparative youth of these soils. Throughout the humid region, subsoils were found to possess amounts of magnesium which were generally comparable with the quantities of this base in the surface soils.

The relatively high levels of magnesium in a number of soils in the vicinity of the Hilo Sugar Company (tables 1 and 2) indicate soils less highly weathered than those of the Hilo and Hamakua coasts as a whole. This suggests that the parent material from which these soils that were higher in magnesium were derived either was younger, or was more resistant to weathering than the volcanic ash that has given rise to the majority of the Hilo and Hamakua coastal soils.

If a comparison is made between the levels of total magnesium and of total calcium in the soils examined (tables 1 and 2), it will be seen that, with a single exception, magnesium is at the higher level. Under the conditions considered, magnesium thus appears to be less susceptible to loss than calcium.

*Ratio of Exchangeable to Total Magnesium*

Relatively small proportions of the magnesium in the soils of the humid regions were present in exchangeable form. Table 1 shows that the values for this relationship ranged from 0.4 to 11 per cent in the cultivated surface soils. The range in the subsoils was similar, from 0.1 to 10 per cent.

More of the total magnesium appeared to be present in exchangeable form in the virgin surface soils than in the corresponding cultivated soils. The situation is apparent from table 2, which shows that the percentages of magnesium in exchangeable form in the virgin surface soils are from about two to nearly seven times as great as those in the adjoining cultivated soils. This finding appears to be in consonance with the fact, already noted, that the virgin soils are at higher exchangeable-magnesium levels than the cultivated soils.

Smaller proportions of total magnesium than of total calcium are present in exchangeable form in the soils studied. This is apparently a natural relationship, and not one induced by liming, as is indicated by the fact that the situation in the virgin soils is similar to that in the agricultural soils.

The proportion of total magnesium present in the soil in exchangeable form appears to be influenced by the rainfall, as may be seen in table 1. The ratio of exchangeable to total magnesium in the surface soils of the Hilo and Hamakua coasts tends to decrease with increasing precipitation, the effect being most marked in the less humid areas. The effect of rainfall on the distribution of magnesium between the two forms is more pronounced in the subsoils. In this horizon the ratio dropped from 10 to about

1 per cent within the precipitation range of 65 to about 115 inches. Above 115 inches there was little further decrease.

## EXCHANGEABLE POTASSIUM

The level of exchangeable potassium in the soil necessary to permit optimum growth of sugarcane has not been determined in Hawaii. Studies by Craig (8), in Mauritius, seem to indicate that sugarcane may suffer a deficiency of potassium when the level of the base in exchangeable form is less than about 0.02 per cent $K_2O$ (approximately 0.4 milliequivalent per 100 grams of soil). This value is of the same order as that obtained by Magistad (29) who found that pineapples in Hawaii did not respond to applications of potash when the level of exchangeable potassium exceeded 0.4 to 0.5 milliequivalent.

Both sugarcane and pineapples have exceptionally high requirements for potash. Heavy fertilization with this nutrient has therefore been the rule on the plantations for many years.

### *Levels of Exchangeable Potassium*

The amounts of exchangeable potassium in the humid-region agricultural soils are extremely variable (table 1). The values for the surface soils range from about 0.1 to 0.8 milliequivalent (omitting a single exceptionally high value at Paauhau), or from about 125 to nearly 1,000 pounds of $K_2O$ per acre-foot of soil. Subsoils in some areas were found to contain smaller quantities of potassium than corresponding surface soils, whereas the reverse was the case in other areas. As will be seen presently, the horizonal distribution of exchangeable potassium in the cultivated soils is related to the rainfall.

An unusual relationship existed between the principal exchangeable bases in some of the more highly leached soils. One of the surface soils (table 1), although only moderately supplied with exchangeable potassium, contained more of this base than of either calcium or magnesium. In the subsurface horizon, at least one-fourth of the soils examined contained higher levels of exchangeable potassium than of either of the other bases. Since the corresponding situation was not observed in any of the virgin soils, it is presumed that the relationship resulted from potash fertilization.

### *Effect of Rainfall on the Horizonal Distribution of Exchangeable Potassium*

The data relative to the Hilo and Hamakua coastal soils indicate that the distribution of exchangeable potassium between the surface and subsurface horizons is related to the rainfall. This relationship is shown in figure 4 where, with the exception of a single nonconforming soil, the ratio

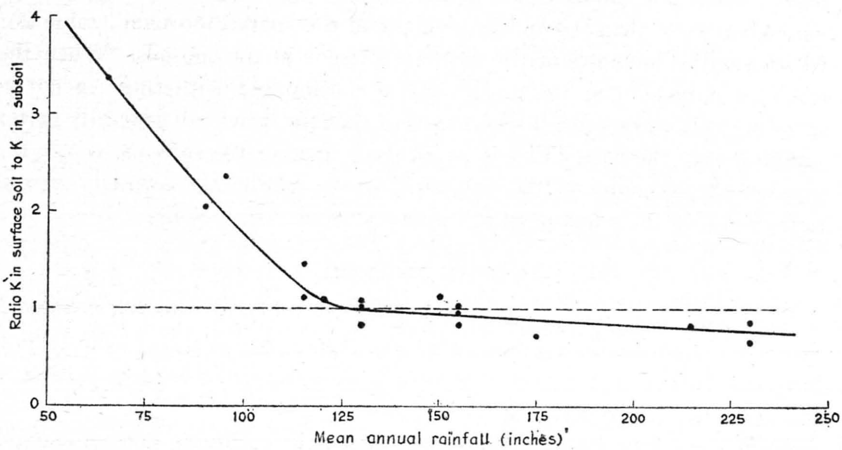


Figure 4.—Curve showing the effect of rainfall on the ratio of exchangeable potassium in the surface soil to exchangeable potassium in the subsoil.

of potassium in the surface soils to that in the subsoils is plotted against the rainfall and a curve drawn to fit the data. The figure shows that in regions of relatively low rainfall, exchangeable potassium in the surface soils is higher than in the corresponding subsoils, as indicated by ratios greater than unity. With increasing precipitation, however, the ratio decreases until at about 125 inches the levels of potassium in the two horizons become equal. Above this amount of rainfall the subsurface horizon contains as much or more exchangeable potassium than the surface soil.

Since the completion of this work, Borden (6) has published a paper dealing with the biological evaluation of subsoil fertility. Borden compared the growth of Sudan grass on surface soils and subsoils from 28 plantations, representing the 4 cane-producing islands. Of the more than 200 subsoils studied by him, only those from the higher rainfall areas, namely, those from the region between Kaiwiki and Waiakea plantations on the Island of Hawaii, produced larger crops of Sudan grass, without added potash, than corresponding surface soils.

The presence of exchangeable potassium in the subsoils in amounts equal to or greater than those in the surface soils does not appear to be a feature of any of the virgin soils examined in this study.

### *Effect of Agricultural Practices Upon the Level of Exchangeable Potassium*

Fertilization associated with the production of sugarcane appears to have increased somewhat the levels of exchangeable potassium in the humid-region soils. The potassium contents of the virgin soils vary from 0.1 to somewhat more than 0.4 milliequivalent in the surface horizon (table 2). Much smaller amounts of the base are present in the subsoils. When the levels of potassium in the virgin soils are compared with those in corresponding cultivated soils, it seems evident that the latter are generally better supplied with the base. This is particularly true of the subsoils, where the supplies of potassium in the cultivated areas are, on the average, several times those in the corresponding horizons of the virgin soils.

## TOTAL POTASSIUM

Total potassium was not determined in the samples obtained in this study. However, analyses for total potassium in the sugarcane soils of the Islands have been made over a period of many years at the experiment station of the Hawaiian Sugar Planters' Association; and these results, assembled and condensed by Van Brocklin (56), indicate values ranging from about 0.3 to 1.0 per cent $K_2O$ for the soils considered in the present study.

## EXCHANGEABLE MANGANESE

Exchangeable manganese (bivalent manganese) and manganese dioxide appear to be the forms of this element which are important from the standpoint of plant nutrition. Studies of Piper (47) have shown that manganese dioxide, although not available to plants directly, is readily changed to the usable manganous form under suitable reducing conditions. Conversely, available manganese may be converted to the unavailable form if conditions favoring oxidation obtain. The oxidation-reduction equilibrium of the soil is thus closely associated with the availability of this element.

The acidity of the soil, also, has been recognized for many years as a factor in the availability of manganese; deficiencies of manganese are more prevalent on neutral and alkaline soils than on acid soils. It may be noted in this connection that Lee and McHargue (27) in their studies of Pahala blight, a chlorotic disorder of sugarcane associated with a deficiency of manganese, found no instance of the disease on acid soils. The findings of McGeorge (36), that soil solutions displaced from soils of pH 6.0 or above contained no manganese, appear to be in line with this observation. So also does the fact that McGeorge (38) successfully controlled Pahala blight through the addition of sulfur to the soil.

Manganese deficiency in sugarcane is not unusual in Hawaii. Martin (33) reported that Pahala blight has been observed on all of the cane-producing islands. It is rarely severe, however. The varying susceptibility of different varieties of sugarcane to this disease suggested to Lee and McHargue that the necessary level of manganese in the soil may be higher for some varieties than for others. The possibility has been suggested by Piper that a soil may be deficient in exchangeable manganese only part of the time, that is, when the soil is fairly dry and conditions favor the formation of manganese dioxide. In support of this view he has pointed out that plants suffer more from manganese deficiency in dry than in wet years.

### *Levels of Exchangeable Manganese*

The quantities of exchangeable manganese in the cultivated soils are shown in table 1. Levels of manganese in the surface soils of the humid regions cover a fairly wide range, from a trace (less than 0.005 milliequivalent) to 0.065 milliequivalent, or from less than 4 to more than 50 pounds MnO per acre-foot of soil. Of the subsoils, only those of Olaa contained more than traces of exchangeable manganese.

Relatively large amounts of exchangeable manganese were found in the drier-region soils of Ewa and Aiea. The levels of manganese in these soils were 0.10 and 0.16 milliequivalent (roughly 90 and 140 pounds MnO per acre-foot) respectively.

The amounts of exchangeable manganese in the virgin soils and in comparable field soils are shown in table 2. The data do not indicate that changes in the levels of exchangeable manganese have resulted from the production of sugarcane on these soils.

## TOTAL MANGANESE

Manganese has been found in Hawaiian lavas in amounts ranging from less than 0.1 to nearly 2 per cent MnO. Manganese minerals are quite susceptible to decomposition and leaching, as is attested by the fact that some lava-derived Hawaiian soils contain only a few hundredths of 1 per cent MnO. At elevations below 1,000 feet, localized areas of alluvial and colluvial soils that contain unusually large amounts of manganese are found. Kelley (24) studied these manganiferous soils at length and found that they contained as much as 9 per cent MnO. Part of the manganese, Kelley observed, was often present in the form of concretions. Manganiferous soils are found on several of the islands, but principally on the Island of Oahu, between the Koolau and Waianae ranges of mountains.

### *Levels of Total Manganese*

Some of the humid-region surface soils contained very small amounts of total manganese (tables 1 and 2), in the neighborhood of 0.04 per cent MnO. Other surface soils of the humid districts, particularly some of those in the neighborhood of Paauhau and Hamakua, contained many times this amount of manganese. Manganese contents of the subsoils were, on the whole, similar to those of the surface soils.

The proportions of total manganese present in exchangeable form in the surface soils studied were very small. In only one instance was the percentage of the base in exchangeable form more than 1.6 per cent. In most of the subsoils, only traces of manganese were present in exchangeable form.

## BASE-EXCHANGE CAPACITY

The base-exchange capacity, or saturation capacity, is a measure of the extent to which the soil is able to take up soluble bases and retain them in exchangeable form. Some soils possess this capacity in only slight degree. Other soils are capable of very great retention of exchangeable bases. The importance of the exchange capacity of the soil in areas of excessive rainfall cannot be overestimated.

The ability to retain exchangeable bases characterizes both the organic and the inorganic fractions of the soil. In soils that are low in organic matter and that contain substantial clay fractions, most of the exchange capacity is frequently associated with the mineral constituents of the soil. In other soils the bulk of the exchange capacity may be resident in the soil organic matter. The latter condition may be the result of a negligible clay fraction, as was found by Peech (45) in light sandy soils of Florida citrus groves. Or, as Craig (8) has found in some lateritic clay soils of Mauritius, it may result from a clay fraction possessing very low base-exchange capacity.

Base-exchange capacities of loessial soils from Colorado, Kansas, and Missouri were found by Jenny and Leonard (23) to increase (logarithmically) with increasing rainfall, the precipitation range being from 14 to 38 inches. Increases in the exchange capacity were attributed to increases both in the organic fraction of the soil and in the inorganic clay fraction. Craig and Halais (10), on the other hand, found that the base-exchange capacity of Mauritius soils, derived from doleritic basalts, decreased with increasing precipitation through the higher rainfall range of 25 to 150 inches. The decrease in exchange capacity observed by these investigators was correlated with a decline in the colloid content of the soil.

In a later study of Mauritius soils, Craig (8) determined separately the exchange capacities of the organic and inorganic fractions of the soils. In this connection he found that the decline in exchange capacity of the soil with increasing rainfall is related not only to a diminishing colloid content of the soil but also to a decreasing exchange capacity of the clay fraction itself. In turn, the loss in exchange capacity of the clay separate was correlated with progressive laterization, as indicated by a diminution of the silica-sesquioxide ratio of the clay and of the whole soil. Craig found that the exchange capacity of the soil organic matter is little influenced by rainfall.

Vanderford (57) has recently published findings which deal with the influence of rainfall on the mineral-exchange capacity of loessial soils from the bluffs of the Mississippi and Missouri rivers. Vanderford found that the capacity of the clay separates to retain exchangeable bases diminished with increasing rainfall through the precipitation range of 20 to 55 inches. Like Craig, he correlated the decrease in exchange capacity of the clay separates not only with rainfall but also with a diminishing silica-sesquioxide ratio.

Base-exchange capacities of soils have not been studied extensively in Hawaii. McGeorge (39) determined the exchange capacities of a number of Kilauea soils and included in the study a few miscellaneous samples, among them one from Olaa. Exchange capacities of one or more pineapple soils from each of the principal islands of the group were determined by Magistad et al. (31).

*Base-Exchange Capacities of the Soils*

The capacities of the cultivated soils studied to retain exchangeable bases are shown in table 1. The base-exchange capacities of the Hilo and Hamakua coastal surface soils, as well as those of Olaa and Waiakea, were high, ranging from approximately 33 to 60 milliequivalents per 100 grams of soil. Base-exchange capacities of the subsoils in this region were lower than those of the surface soils. As will appear later, these differences are principally the result of smaller quantities of organic matter in the lower horizon. Exchange capacities of the Kilauea soils were considerably lower than those of the Hilo and Hamakua coastal soils and were of the same order as the exchange capacities obtained earlier by McGeorge.

A consideration of the low-rainfall soils of Oahu shows that two of the soils examined possessed exchange capacities that were relatively low, that is, in the neighborhood of 15 milliequivalents. The other two soils from this region were much higher—as high, in fact, as some of the humid-region soils of the Island of Hawaii.

*Base-Exchange Capacities of the Soils in Relation to Rainfall*

A relationship between rainfall and the exchange capacities of the Hilo and Hamakua coastal surface soils is shown in figure 5. The exchange capacities of the soils of this region appear to decrease with increasing precipitation. Statistical analysis of the data indicates that this relationship is significant. The base-exchange capacities of the subsoils also tend to decrease

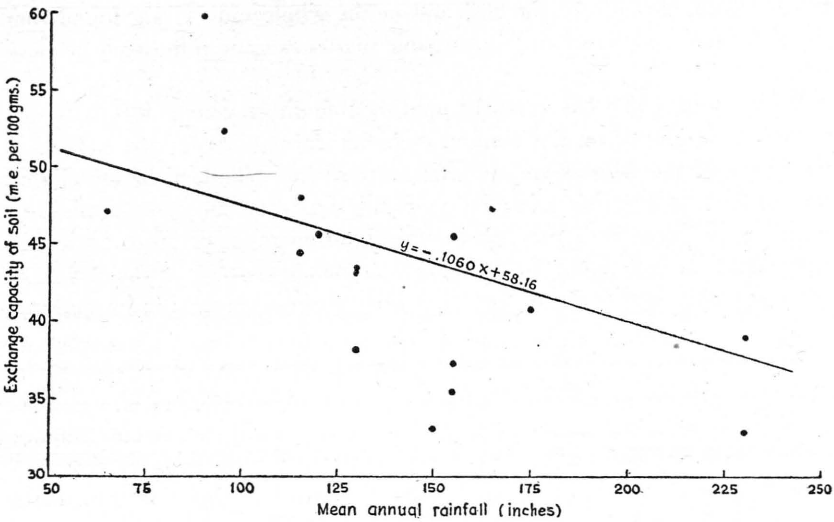


**Figure 5.—Relation between rainfall and the base-exchange capacities of the surface soils.**

with increasing rainfall, but the relationship, in this instance, was not significant. These results appear to be in accord with those obtained by Craig and Halais (10) but not with those of Jenny and Leonard (23), as might be expected from a consideration of the precipitation ranges involved. It will be seen subsequently that the diminution in base-exchange capacities of the soils with increasing precipitation is the result of the destructive effect of rainfall upon the mineral-exchange capacities of the soils, as the organic-exchange capacities are seemingly independent of the rainfall.

*Base-Exchange Capacities of the Mineral Fractions of the Soils*

The base-exchange capacities of the mineral fractions of the humid-region surface soils were found to vary widely. The range is from 2.6 to 28 milliequivalents per 100 grams of organic-matter-free soil. The mineral-exchange capacities of the subsoils were generally somewhat lower than those of the corresponding surface soils and varied from less than 1 to 22 milliequivalents.

The data pertaining to the Hilo and Hamakua coastal soils show that the exchange capacities of the inorganic fractions of these soils decrease with increasing rainfall. This relationship is brought to light in figure 6, where the mineral-exchange capacities are plotted against the rainfall. The relationship was found to be statistically significant, as was also the correspond-

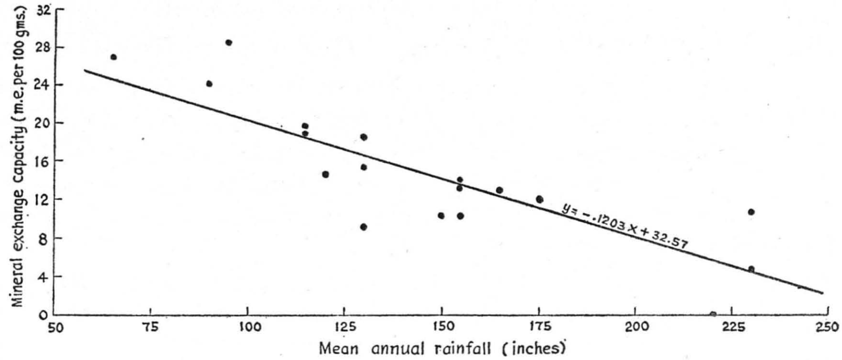


Figure 6.—Decrease of mineral-exchange capacity with rainfall in surface soils.

ing relationship for the subsoils. It is apparent that high rainfall has adversely affected the base-exchange capacities of the mineral fractions of the soils. These results are similar to those obtained by Craig (8).

*Base-Exchange Capacities of the Soil Organic Matter*

A wide range of values for the base-exchange capacities of soil organic matter has been reported. Not only have values in widely separated areas been found to vary, but equally wide fluctuations have been found within a single soil profile, as is evidenced, for example, by the studies of Tedrow and Gillam (53).

The base-exchange capacities of the organic fractions of the soils studied are shown in table 1. It is apparent that the exchange capacity of this material is far higher than that of the mineral fraction of the soil. At the same time it, too, is quite variable. With the exception of a single unusually low value on Oahu, the exchange capacity of the organic matter in the surface soils varied from 135 to about 250 milliequivalents, with a mean value of about 200. The range in the subsoils is still wider (from 58 to 323 milliequivalents).

It appears from these results that the base-exchange capacities of soil organic matter formed under Hawaiian conditions are not essentially different from those of organic matter in temperate-zone soils, as judged, for example, by the results of Olson and Bray (43), Peech (45), and others. Values somewhat higher than the mean of the present results were obtained by Craig (8) for the tropical soils of Mauritius.

Little or no relationship is apparent between the exchange capacity of the organic matter and rainfall. This is in accord with results in Mauritius.

*Exchange Capacities of the Organic Matter in Relation to the Carbon-Nitrogen Ratios*

There appears to be a relationship between the base-exchange capacities of the soil organic matter and the carbon-nitrogen ratios. This relationship, based upon the surface soils of the Hilo and Hamakua coasts, is illustrated in figure 7. This figure shows that, as the carbon-nitrogen ratios increase, the exchange capacities of the organic matter decrease. This relationship was found to possess statistical significance.

Whether the relationship between the capacity of the soil organic matter to retain exchangeable bases and the carbon-nitrogen ratio is functional or merely associative, is not clear. It is, however, of interest in view of the work of Waksman and Iyer (61) on the base-exchange capacity of the ligno-proteins. These workers showed that lignin, the principal constituent of soil organic matter, possesses a low base-exchange capacity, but in combination with proteins it may possess a relatively high exchange capacity. Moreover, they showed that the base-exchange capacities of ligno-protein complexes increase with increasing protein content. Conceivably, such a relationship might explain the decrease in base-exchange capacity of the soil organic matter with increasing carbon-nitrogen ratio.

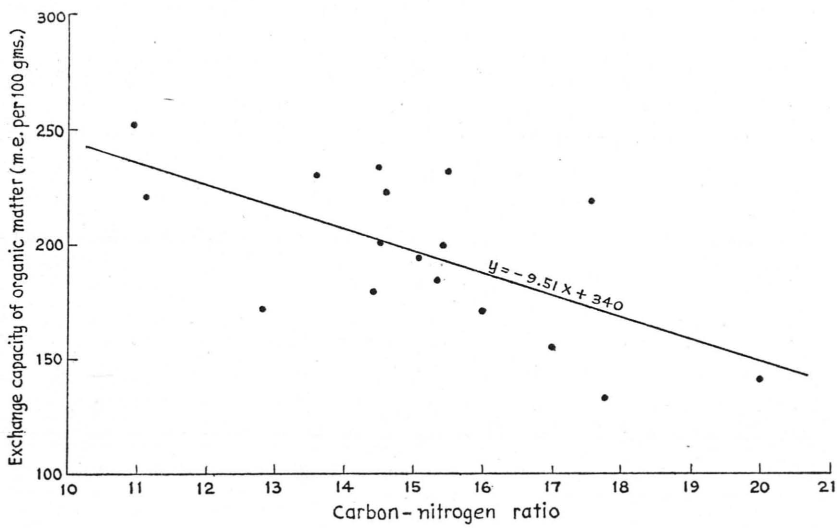


**Figure 7.—Exchange capacity of the soil organic matter in relation to the carbon-nitrogen ratio in surface soils.**

### *Effect of Organic Matter on the Base-Exchange Capacities of the Soils*

The magnitude of the effect of organic matter upon the base-exchange capacities of the soils examined is extremely varied. The relatively small amounts of organic matter in the Oahu soils have added only slightly, or to the extent of about 3 milliequivalents, to the exchange capacities of the mineral fractions of these soils. A wholly different situation exists in the soils of the humid regions. There the base-exchange capacity resident in the soil organic matter amounted, in the surface soils, to from 22 to about 50 milliequivalents per 100 grams of soil. Since the subsoils contain smaller amounts of organic matter than the surface soils, this material added correspondingly less to the exchange capacity of the lower horizon. The organic-matter fractions of the subsoils were responsible for from 5 to a little less than 40 milliequivalents of exchange capacity per 100 grams of soil.

The results discussed above, expressed as percentages of the base-exchange capacities of the entire soils, are shown in table 1. The organic matter accounts for from 13 to 27 per cent of the exchange capacities of the Oahu surface soils. In the surface soils of the humid regions, from about 50 to 90 per cent of the exchange capacity is resident in the organic matter. In the humid-region subsoils, values cover a range from about 25 to almost 95 per cent. It is apparent that the position of organic matter in the exchange relationships of the humid-region soils is one of great importance.

Further evidence of a relationship between rainfall and the role of organic matter in the base-exchange relationships of Hawaiian soils is seen in figure 8, in which the percentages of the total base-exchange capacities resident in the organic-matter fractions of the Hilo and Hamakua coastal surface soils are plotted against rainfall. The diagram shows that in the driest portion of this region the exchange capacity of the soil is about equally divided between the mineral and organic fractions of the soil. With increasing precipitation, however, the proportions of the exchange capacity resident in the organic matter increase, attaining much higher values in areas of greater rainfall. This relationship was found to be statistically significant.

## BASE SATURATION

The degree of base saturation of a soil is a measure of the amount of exchangeable bases which the soil contains in relation to the base-exchange capacity, that is, the amount which it is capable of containing. It is usually expressed upon a percentage basis. The degree of base saturation of a soil offers a general indication of the extent to which the soil has been leached. It is this property of the soil which determines, in large measure, the pH of the soil. The degree of base saturation of the soil has been shown by Craig and Halais (10) and by others to be a function of the rainfall. Craig

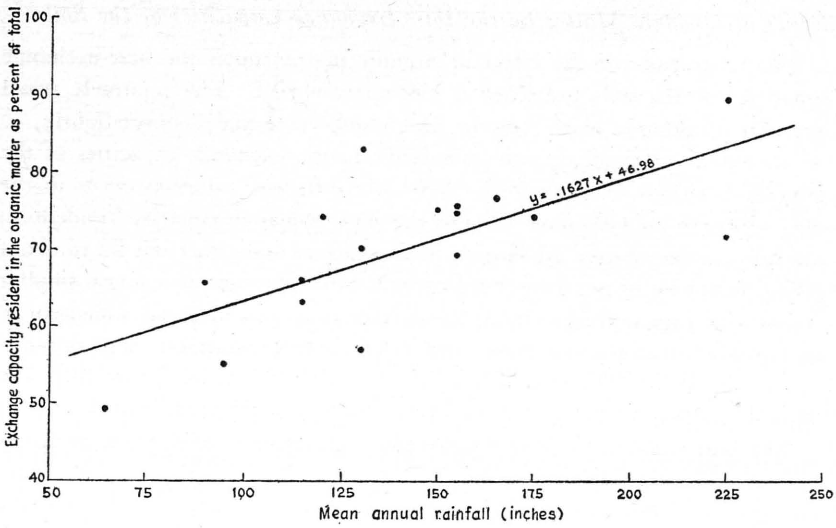


**Figure 8.—Relation between rainfall and the proportion of the base-exchange capacity resident in the soil organic matter.**

and Halais found that the degree of base saturation progressively decreased with increasing rainfall within the precipitation range of 25 to 150 inches.

The availability of exchangeable bases has been shown by Jenny and Ayers (22), Albrecht and Smith (1), and others to be related to the degree of base saturation. These workers found that as the degree of saturation with respect to a particular base decreased, the availability of the base to plants likewise decreased. In so far as calcium is concerned, these observations have been substantiated by results obtained in this laboratory.

It has been shown by Peech and Bradfield (46), Peech (45), and for Hawaiian soils by the writer (5), that the ability of the soil to sorb added neutral potash salts increases with increments in base saturation. The writer found that the sorption of ammonium similarly responded to the degree of base saturation of the soil.

### *Base Saturation of the Soils*

The extent to which the soils studied are saturated with bases is indicated in table 1. The degrees of saturation shown in the table are based upon the sum of the exchangeable calcium, magnesium, and potassium contents of the soils. The omission of sodium probably does not appreciably affect the results. Reference to the table indicates degrees of base saturation ranging from less than 5 to nearly 100 per cent. Base saturation in the humid-region

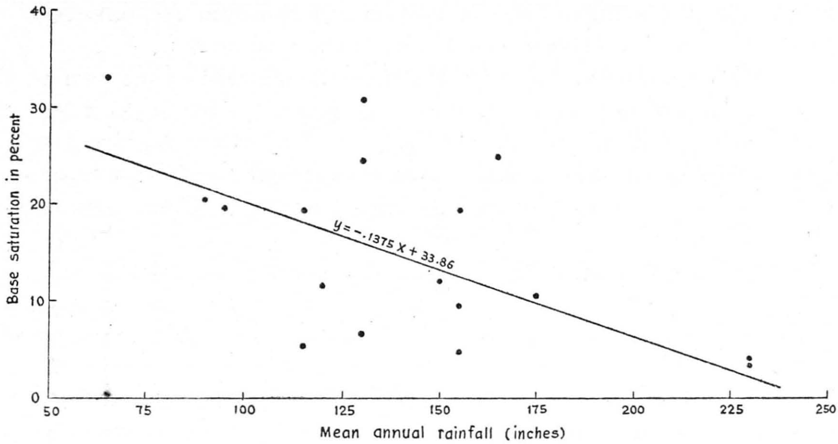


**Figure 9.—Influence of rainfall on the degree of base saturation of the surface soils.**

soils covers a much narrower range. With the exception of a single high value, the range in the latter soils is roughly from 4 to 33 per cent in the surface soils and from 2.5 to 38 per cent in the subsoils. The very low saturation values observed in some of the soils examined suggest, in light of the earlier discussion, that these soils may not be functioning at maximum efficiency in their retention of potassium and ammonium when these bases are applied as neutral or nearly neutral salts.

The effect of rainfall on the degree of base saturation of the cultivated surface soils of the Hilo and Hamakua coasts is illustrated in figure 9. The diagram shows that the degrees of saturation tend to be highest in areas of low rainfall and lowest in those of high rainfall. The wide fluctuations in degrees of saturation indicated in the figure for a given amount of rainfall presumably reflect, in some degree, the liming which many of the soils of this region have received. The degree of base saturation in the subsoils also decreased with increasing precipitation. The relationships in both surface and subsurface horizons were found to have statistical significance. The results support those previously reported by Craig and Halais and by others.

## SOIL ACIDITY

The acidity of the soil may be considered from two standpoints, namely, total or titratable acidity, and intensity of acidity, or pH.

Total acidity is a measure of the neutralizable hydrogen in the soil. It includes the exchangeable hydrogen associated with the inorganic and organic exchange materials of the soil and also the ionized and ionizable hydrogen of the soil solution. The latter forms of hydrogen are, however, responsible for only an insignificant portion of the total acidity.

Exchangeable hydrogen dominates the exchange material of the humid-region soils, as seen in the low degrees of base saturation which characterize these soils. Many of the soils considered in this study, possessing low degrees of base saturation and high exchange capacities, would require the addition of large quantities of lime to bring about a condition approximating neutrality.

The pH of a soil measures the intensity of the acidity, but gives no indication of the total acidity, nor of the amount of lime required to neutralize the soil. The pH of a soil may be looked upon as expressing the relative amounts of exchangeable bases and of exchangeable hydrogen in that soil. The identical pH in another soil, one in which the exchange materials have different characteristics, would, however, express a different relationship between exchangeable bases and exchangeable hydrogen.

Every plant is commonly supposed to grow best within certain pH limits. Spurway (52), in his compilation of soil-reaction preferences for plants, sets the optimum pH range for sugarcane at from 6.0 to 8.0, with a minimum limit of 5.0. Spurway's minimum pH limit is seemingly too high for Hawaiian conditions. The writer (4) obtained apparently normal growth of sugarcane in potted soil of pH 4.6. Moreover, as table 1 shows, two of the surface soils sampled in this study possessed pH values of 4.5 and 4.7, yet, so far as is known, the high acidity of these soils has not resulted in impaired growth of sugarcane. So far as acidity, in itself, is concerned, it may be noted that Martin (32) obtained satisfactory growth of sugarcane in nutrient solutions of pH 4.0. There appears to be no evidence at hand to indicate that the pH of any of the soils of the Islands is so low as to cause direct injury to sugarcane. Possible secondary effects of high acidity, however, merit consideration and will be referred to in a later section.

### *Acidity of the Soils (pH)*

All of the humid-district soils examined were acid. The pH range in the surface soils was from 4.5 to 6.0, as indicated in tables 1 and 2. With very few exceptions, the subsoils were less acid than the corresponding surface soils. Values in the subsoils ranged from pH 4.7 to pH 6.2.

The generally higher pH values of the subsoils, as compared with corresponding surface soils, cannot be accounted for on the basis of higher levels of exchangeable bases in the lower horizon. Thus as the tables show, the subsoils with a single exception contain lower levels of exchangeable bases than the surface soils. Nor can the less acid condition of the subsoils be attributed in all cases to their lower base-exchange capacities, in themselves, for base saturation is more often at a lower level in the subsurface horizon than in the surface horizon. It seems necessary, therefore, to look to the *nature* of the exchange materials in the two horizons for an explanation.

As will be seen later, larger quantities of organic matter are present in the surface soils than in the subsoils. Moreover, as will also be seen in a subsequent section, the ultimate pH of the soil is lowered by the presence of organic matter. If the pH of the soil is similarly lowered by organic matter, it would be expected that the depressing effect would be more pronounced in the surface horizon than in the subsoil. It seems probable, therefore, that the low pH values of the surfaces soils, as compared with those of the subsoils, are primarily due to the higher content of organic matter.

### *Effect of Agricultural Practices on the pH Values of the Soils*

The effect of agricultural practices on the pH values of the soils of the Hilo and Hamakua coasts is indicated in table 2. Comparison of the data for the cultivated and virgin soil samples shows that the pH values of the cultivated soils, for both surface and subsurface horizons, are in every instance higher than those of corresponding virgin soils. In 5 of the 10 pairs, the differences are only 0.1 and 0.2 pH unit and hence must be considered of doubtful significance. In the remaining 5 pairs, however, the agricultural soils are less acid than the virgin soils by from 0.4 to 0.8 pH unit. There appears, therefore, to be some evidence that the acidity of the soils has decreased as a result of their conversion to agricultural use.

The reason for the less acid condition of the cultivated soils is not apparent at once. Consideration of the data does not reveal consistently higher levels of exchangeable bases in the cultivated soils, as might be expected in view of the less acid condition found there. When, however, the levels of organic matter in the virgin and cultivated soils are considered, it will be seen that this material is generally lower in the cultivated soils. It appears likely, in view of the influence of organic matter on the ultimate pH of the soil, which will be considered on pages 30 and 31, that the less acid condition of the cultivated soils is largely the result of lower levels of organic matter.

### *Ultimate pH*

When exchangeable bases are removed from a soil by electrodialysis, the positions occupied by the bases in the exchange material of the soil are assumed by hydrogen ions derived by hydrolysis from the water. When all of the exchangeable bases have been removed, the exchange material of the soil contains all the exchangeable hydrogen it is capable of retaining and hence the soil has reached its maximum acidity. The pH of the soil in this hydrogen-saturated condition is referred to as the "ultimate" pH and represents the final stage in leaching, so far as the exchangeable bases are concerned. Once the acidity of the soil has reached the ultimate pH, no amount of leaching can render it more acid.

There is evidence that under some conditions the ultimate pH of the soil may be influenced by the soil organic matter. Prince, Toth, and Blair (48) observed lower ultimate pH values in the 0- to 2-inch horizon than in lower horizons, and attributed the lower values, in part, to the higher organic-matter content of the surface layer. Since the present study was completed, a paper has been published by Mehlich (40) which shows clearly the pronounced influence of organic matter on the pH values of certain types of soil. Mehlich found that the effect of organic matter was to lower the pH values (for a given degree of saturation) of soils whose clay fractions consisted of certain minerals of the kaolin group and to raise the pH values of soils containing clay of the montmorillonite type.

### *Ultimate pH Values of the Soils*

Ultimate pH values of the cultivated soils are quite variable (table 1), ranging in the surface soils from 3.6 to 4.7. The lowest values are found for the Kauai soils. Ultimate pH values of the subsoils were consistently higher than the values for the corresponding surface soils. Values for the subsoils varied from 4.5 to 5.4.

Comparison of the proximity of the present pH values of the humid-region cultivated soils to the ultimate values shows that some of the soils are not far removed from a condition of ultimate acidity. A number of the Hilo and Hamakua coastal surface soils are within 0.5 pH unit of ultimate acidity, and some of the subsoils of this region are even closer to this condition. It is thus apparent that some of the humid-region soils, especially the subsoils, are nearly as acid as it is possible for them to become.

It may be appropriate to consider the probability of injury to the crop, should degrees of acidity approximating the ultimate pH be permitted to develop in the humid-region soils. The surface soils of the humid region of the Island of Hawaii possess ultimate pH values ranging from 4.0 to 4.7. It appears doubtful if any of these soils, while containing levels of calcium, magnesium, and potassium sufficient to meet the nutrient needs of sugarcane, could become so acid as to result in direct acid injury to the crop. Since none of the subsoils of this region is apparently capable of becoming more acid than pH 4.5, it seems still less likely that injurious degrees of acidity could develop in the soils of this horizon. However, it cannot be safely assumed that none of the soils of the humid regions could become sufficiently acid to result in injury to the cane. The ultimate pH values of the two samples of surface soil from Kilauea, for example, were 3.6 and 3.7. Little is known regarding the growth of sugarcane in soil at such pH levels.

Although decreases in the pH values of some of the high-rainfall soils to points approximating the ultimate pH values would presumably not result in direct injury to the cane plant, the possibility of indirect effects must be considered. One possible indirect effect of high acidity is toxic concentrations of absorbable aluminum. McGeorge (37) demonstrated aluminum injury to sugarcane in some of the Hamakua coastal soils where the pH values were no lower than 5.5. Normal growth of cane in other soils of this region, where the pH values are at least as low, suggests differences in soils in this respect. Instances were cited earlier in which sugarcane produced apparently normal growth at pH values considerably below 5.5.

*Influence of Organic Matter on the Ultimate pH of the Soil*

The consistently lower ultimate pH values of the surface soils, as compared with the subsoils, together with the higher levels of organic matter in the upper horizon, point to organic matter as a factor influencing the ultimate pH of the soil. In order to determine to what extent, if at all, this material was responsible for the ultimate pH values of the soils and to ascertain at the same time the ultimate pH values of the mineral fractions of the soils, the following experiment was conducted.

A number of soils were either ignited or treated with $H_2O_2$ in order to destroy the organic matter. Ignitions were carried out at 275° C. and continued for a period of 48 hours. Where $H_2O_2$ was used to effect the destruction of the organic matter, the soils were treated several times with the reagent in concentrated form (30 per cent). Following destruction of the organic matter, the soils were electrodialysed to constant pH.

The effects of the foregoing treatments upon the ultimate pH values of the soils are shown in table 3, in which the data are arranged according to the increasing organic-matter content of the soils. The last column of the table shows that by elimination of the organic matter the ultimate pH was increased by from 0.3 to 1.9 pH units, and that the increases were generally greater, the higher the organic-matter content of the soil. It is apparent from these results that the effect of organic matter is to depress the ultimate pH. This depression doubtless accounts in large measure for the lower ultimate pH values of the surface soils as compared with the subsoils.

The foregoing observation is in accord with the findings of Prince et al. (48). It is also in harmony with the results of Mehlich (40), if it be assumed that the alumino-silicate clays present in the soils studied are principally of the kaolin type. Such evidence as is at hand indicates that this is the case.

An effect of the elimination of the organic matter, it may be noted in table 3, was to bring the ultimate pH values of surface and corresponding subsoils closer together. This would be expected in view of the differentiation in levels of organic matter between the two horizons.

The mineral fractions of some of the soils possess ultimate pH values that are unusually high. The table shows that values are as high as pH 6.3. Such values suggest clay fractions high in iron and aluminum oxides and low in inorganic acidoid content.

## ORGANIC MATTER

It has been shown that organic matter is important in the high-rainfall soils because it is responsible for much of the capacity of these soils to retain exchangeable bases and also because it influences the pH of the soil. Organic matter is recognized also as the source of practically all of the nitrogen that these soils contain. Moreover, one-fourth or more of the total phosphorus in Hawaiian soils is present in organic forms, as has been shown by Dean (13). Organic matter does not, however, appear to be an agent of consequence in the fixation of phosphates by soils. It may be assumed, therefore, that the exceptionally high phosphate-fixing capacity of the Hilo and Hamakua coastal soils (2) is not attributable to this fraction of the soil. In addition to the functions already noted, organic matter influences soil structure and temperature, the moisture-holding capacity of the soil, and the oxidation-reduction potential, which Piper (47) has shown to be an important factor in the availability of manganese.

Virgin soils of the humid regions support native vegetation, which in high-rainfall areas is very heavy. However, the generally high organic-matter content of the humid-region soils is probably the result not only of the luxuriant native vegetation that once covered these soils, but also of slow decomposition of the organic matter. Burgess (7) and Richter (50) concluded from their studies of Hawaiian soils that semianaerobic conditions prevail in many of the soils of the maximum and near-maximum rainfall districts, largely because of excessive soil moisture. Evidence of anaerobiosis in the soils of high-rainfall areas was also obtained by Kelley (25) in his studies of ammonification and nitrification. To the degree that this condition has existed, it has doubtless impeded oxidation and hence loss of the organic matter. It is probable also that the low levels of exchangeable bases in these soils, together with the resulting low pH values, have been inimical to intense bacterial activity.

Extremely wide differences in levels of organic matter are found in Hawaiian soils. These differences appear to be related both to temperature and to rainfall. Thus Dean (14) found that the organic matter content of Hawaiian soils increased with increasing rainfall but decreased with increasing temperature.

Organic matter in Hawaiian soils is by no means restricted to the surface layer of the soil, as substantial quantities of this material are frequently present at considerable depths. Penetration of the soil by organic matter has been recorded by Hough and his associates (18, 19) in their studies of Hawaiian soil profiles. These investigators attributed the presence of unusual amounts of organic matter in the lower horizons, in part, to high rainfall. A low degree of dispersion of the clay particles, resulting in a permeable condition of the soil, was also believed by these workers to expedite the downward movement of colloidal organic material.

*Levels of Organic Matter*

The levels of organic matter in the cultivated soils are shown in table 1. It will be observed that the smallest amounts of organic matter are present in the drier Oahu soils, where the range is from about 2 to 6 per cent. In the humid-region surface soils, the levels of organic matter are higher, or from about 7 to nearly 27 per cent. The Waiakea and Olaa soils contain the highest amounts.

With a single exception the subsoils contained smaller amounts of organic matter than the surface soils. Of the humid region subsoils, those of Kauai were lowest in organic matter. Higher amounts of this material were found in the subsoils of the Hilo and Hamakua coasts, and the highest levels in the samples from Olaa. Levels of organic matter in the humid-region subsoils ranged from about 2.5 to 17 per cent.

*Influence of Sugarcane Production on the Levels of Soil Organic Matter*

In a stabilized soil the rate at which plant material is added to the soil is balanced by the rate of decomposition, and the level of organic matter remains relatively constant. If, however, some factor influencing the equilibrium is altered, as when a soil is placed under cultivation, a new set of conditions is established and the level of organic matter in the soil tends toward a new equilibrium, one which is in harmony with the new set of circumstances. It frequently happens that when a virgin soil is converted to agricultural use, the amount of organic material in the soil gradually diminishes, possibly becoming stabilized at a lower level.

The amount of organic material returned to sugarcane soils is a small part of that produced. The practice on Hawaiian sugar plantations is to fire the cane fields immediately prior to harvest in order to eliminate the trash, principally dead leaves, which has accumulated in the course of the growing period. This practice simplifies the harvest of the millable cane.

Subsequent to the harvest, the remaining non-millable portions of the crop are also destroyed in large part by burning. Although the loss of nutrients through this practice is probably negligible, except in the case of nitrogen, very little organic matter from the aerial portions of the crop is returned to the soil, except as wet weather interferes with the burning of the trash. Where ratooning of the crop is practiced, as in Hawaii, the roots of the cane plant are not seriously disturbed mechanically except at intervals of 10 to 15 years, when the fields are plowed and replanted. Although the roots are not destroyed at harvest, except as indicated, there is nevertheless, according to Evans (16), a gradual sloughing of the old roots as the succeeding crop develops its own root system. To the extent that this process occurs, fresh plant material is added to the supply of soil organic matter.

McGeorge (35), in an effort to determine whether the level of carbon was decreasing in sugarcane soils, analyzed a number of virgin and adjacent field soils at Ewa plantation for this constituent. He obtained an average value of 1.30 per cent in the cultivated soils and 1.37 per cent in the virgin soils. This difference was too small to have significance, and McGeorge concluded that the quantities of plant residues returned to the soil had been sufficient to offset the decomposition of organic matter in these soils.

Dean (12), in a study of organic matter in pineapple soils, obtained different results. He found that the effect of many years of pineapple production had been to lower the supply of organic matter in the soil. The further observation was made that the organic matter in the cultivated soils had apparently become stabilized at a lower level.

In the light of the foregoing observations it may prove of interest to consider the changes in organic-matter content of the soils considered in this study that have resulted from replacement of the native vegetative cover with sugarcane. Table 2 shows that the levels of organic matter in the samples from areas of broken forest, or of fern and grass, do not differ greatly from those in the corresponding field samples, although there is some evidence of higher values in the virgin soils. The amounts of organic matter in the forested soils, on the other hand, are much higher than those in corresponding cultivated soils, roughly by increments of 9 and 14 per cent in the surface soils and 7 and 8 per cent in the subsoils. Although the number of comparisons is small, there appears to be some evidence that placing these soils under cultivation has resulted in a diminution in the level of organic matter. To what extent the observed decrease is the result of smaller additions of fresh plant material to the soil and of more rapid decomposition of the organic matter under a system of cane production, and to what extent it is the result of erosion of the surface soil, is not known.

## NITROGEN

The nitrogen content of the soil, like the organic matter, appears to be largely determined by climatic factors. Thus Dean (14), in his study of Hawaiian soils, showed that the level of nitrogen is related to both temperature and rainfall. He found that the amount of soil nitrogen increased with increasing rainfall and decreased with increasing temperature.

The nitrogen contents of Hawaiian soils cover a wide range and are very high in some areas, as would be expected from the preceding consideration of the organic-matter content of the soils. Although the levels of total nitrogen in the soil are frequently high, only very small proportions of the nitrogen are available to plants. In their studies of mineralizable nitrogen, Fukunaga and Dean (17) found wide differences in the abilities of Hawaiian soils to supply this element in utilizable forms. Such evidence as is at hand indicates that the release of nitrogen proceeds more rapidly in the soils of the humid regions than in those of the relatively dry areas. Rarely, however, is the conversion of organic nitrogen to inorganic forms sufficiently rapid to meet the requirements of economic crops for this nutrient. Both sugarcane and pineapples are heavily fertilized with nitrogen under all conditions.

### *Levels of Nitrogen*

Table 1 indicates a wide variation in the levels of nitrogen in the cultivated soils. The lowest levels of this element are in the Oahu and Kauai soils, where the range in the surface soils is from 0.1 to 0.3 per cent. Larger amounts of nitrogen are present in the Hilo and Hamakua coastal soils (0.45 to 0.83 per cent) and the highest amounts (0.9 to 1.0 per cent) in the soils of Waiakea and Olaa plantations. A similar pattern obtained in distribution of nitrogen in the subsurface horizons. Nitrogen in the subsoils varied from 0.07 to 0.70 per cent.

The nitrogen contents of virgin soils from areas of broken forest or of fern and grass are of about the same order as those in the corresponding cultivated soils (table 2). The levels of nitrogen in the forested soils, however, are much higher than in comparable cultivated soils. As in the case of the organic matter, there appears to be limited evidence that the production of sugarcane has resulted in reduced levels of nitrogen in the soils of the Hilo and Hamakua coasts.

## CARBON-NITROGEN RATIOS

Carbon-nitrogen ratios of temperate-zone soils appear to be in the neighborhood of 10 to 12 (21, 42). Carbon-nitrogen ratios of Hawaiian soils depart considerably from this range of values. In a study by Dean (14) of cultivated and virgin soils at elevations ranging from near sea level to 6,500 feet, carbon-nitrogen ratios were found to range from about 8 to 19.

The carbon-nitrogen ratios of Hawaiian soils appear to be related to the rainfall. Thus it was found (14) that the carbon-nitrogen ratio increases with increasing precipitation. A similar relationship has been established by Craig and Halais (10) for the soils of Mauritius.

In their studies of profile development in Hawaiian soils, Hough, et al. (19) observed increasing carbon-nitrogen ratios downward in profiles developed under 80 to 140 inches of rain. This change in the composition of the organic matter with depth, they believed, characterized the podzolic type of Hawaiian soils.

*Carbon-Nitrogen Ratios of the Soils*

Carbon-nitrogen ratios in the surface horizons of the soils, as a whole, range from about 9 to 20 (tables 1 and 2). The range in the humid-region soils is slightly narrower, or from about 11 to 20. These results are similar to those obtained by Dean.

Carbon-nitrogen ratios in the subsurface horizon of the humid-region soils ranged between the limits of 11 and 26. Values for the subsoils were generally somewhat higher than for corresponding surface soils, and for the Hilo and Hamakua coastal area the difference was found to be significant. In some measure, these results appear to support the observations of Hough and his coworkers.

The data relative to the agricultural soils of the Hilo and Hamakua coasts indicate clear-cut relationships between rainfall and the carbon-nitrogen ratios of both surface and subsurface horizons. The relationship, in the case of the surface soils, is illustrated in the scatter diagram of figure 10, which

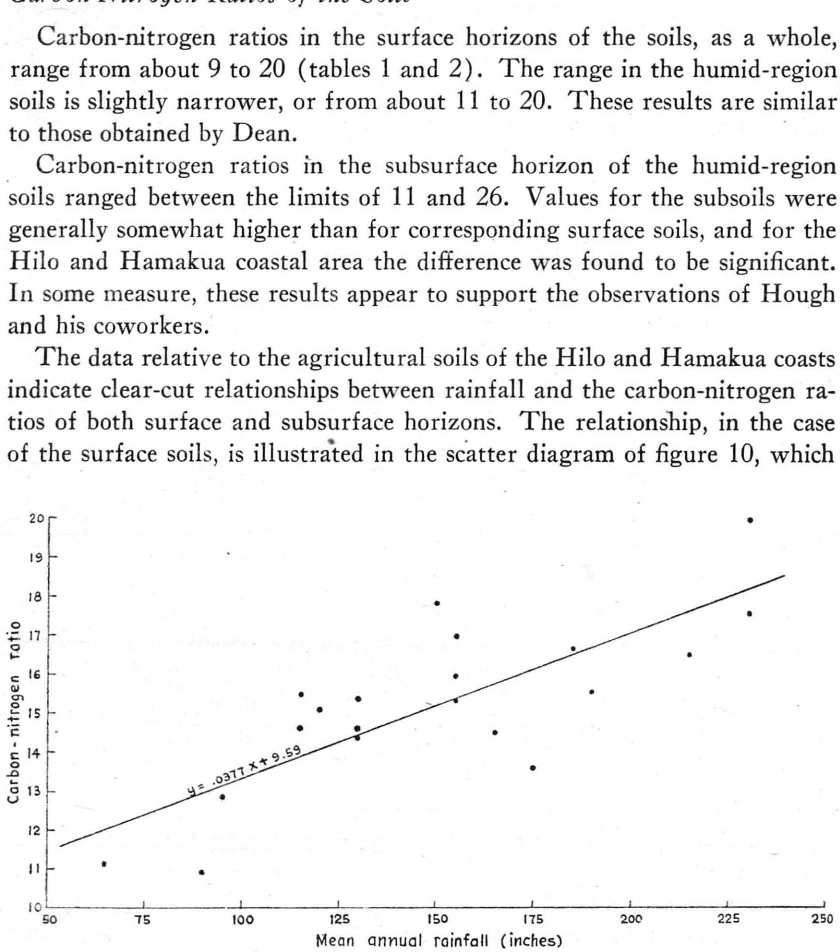


**Figure 10.—Increase in the carbon-nitrogen ratio of the surface soils with rainfall.**

shows that the carbon-nitrogen ratio of the soil organic matter is lowest in areas of least rainfall and increases as the precipitation increases. This relationship was found to be statistically significant. The corresponding relationship for the subsurface horizon was also found to possess statistical significance.

## SUMMARY

Substantial areas of economically vital agricultural soils in the Hawaiian Islands are subject to heavy rainfall and hence to severe leaching. If satisfactory economic crops are to be produced indefinitely on such soils, a knowledge of those properties of the soils which are closely related to their productivity is essential. Accordingly, a study was made embracing the determination of the following properties of the soils: Exchangeable and total bases, base-exchange capacities (mineral and organic fractions), pH, ultimate pH, organic matter, nitrogen, and derived data. The results of the study may be summarized as follows:

Some of the soils were well supplied with exchangeable calcium and magnesium. Other soils contained very low levels of the bases—in the neighborhood of 0.5 milliequivalent per 100 grams.

Levels of exchangeable calcium and magnesium diminished with increasing rainfall.

Exchangeable magnesium existed at lower levels in the cultivated soils than in adjoining virgin soils.

From 2 to 57 per cent of the calcium and from 0.4 to 11 per cent of the magnesium in the surface soils was present in exchangeable form. The ratios of exchangeable to total calcium and of exchangeable to total magnesium decreased with increasing precipitation.

Exchangeable potassium in the surface soils varied from 0.1 to 0.8 milliequivalent, or roughly from 125 to 1,000 pounds $K_2O$ per acre-foot of soil. Below about 125 inches of rain the subsoils contained less potassium than the surface soils. Above this point the subsoils, except in virgin areas, contained higher levels of potassium than the surface soils.

Exchangeable potassium appears to be at higher levels in the cultivated soils than in adjoining virgin soils.

Exchangeable manganese was present in the surface soils in amounts ranging from less than 0.005 milliequivalent to 0.065 milliequivalent (less than 4 to more than 50 pounds MnO per acre-foot of soil). From a trace to about 1.5 per cent of the total manganese was present in exchangeable form.

Capacities of the surface soils to retain exchangeable bases were generally high, ranging from about 20 to 60 milliequivalents. Exchange capacities of the soils diminished with increasing precipitation.

The exchange capacity of the soil organic matter averaged approximately 200 milliequivalents per 100 grams. From about 50 to 90 per cent of the exchange capacities of the surface soils was associated with the organic matter. The proportion of the exchange capacity of the soil resident in the organic matter increased with increasing rainfall.

The base-exchange capacity of the soil organic matter declined as the carbon-nitrogen ratio increased.

Mineral-exchange capacities ranged from about 2 to 28 milliequivalents per 100 grams of organic-matter-free soil. The exchange capacity of the mineral fraction decreased with increasing rainfall.

Base saturation varied between 4 and 33 per cent in the surface soils and between 2.5 and 38 per cent in the subsoils. Base saturation decreased with increasing precipitation.

Subsoils were generally less acid than corresponding surface soils. This was not the result of higher levels of exchangeable bases in the lower horizon, but apparently of lower levels of organic matter.

Ultimate pH values of the surface soils ranged from 3.6 to 4.7. Values for the subsoils were higher than values for the corresponding surface soils. Several surface soils were within 0.5 pH unit of ultimate acidity, and some subsoils were even closer to this condition. Other soils were far removed from a condition of ultimate acidity.

Destruction of the organic matter raised the ultimate pH values of the soils by from 0.3 to 1.9 pH units.

Ultimate pH values of the mineral fractions ranged from 4.6 to 6.3.

Organic matter ranged from 7 to 27 per cent in the surface soils. Some evidence was obtained that levels of organic matter are lower in the cultivated soils than in comparable virgin soils.

Levels of nitrogen ranged from about 0.2 to 1.0 per cent in the surface soils. The nitrogen content of the soil appeared to have been lowered as a result of cropping.

Carbon-nitrogen ratios ranged from 11 to 20 in the surface soils and from 11 to 26 in the subsoils. They increased with increasing rainfall in both surface and subsurface horizons.

The influence of rainfall upon certain properties of the soil was more pronounced in the lower than in the higher precipitation range.

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TABLE 1. Chemical properties of the humid-region agricultural soils

| Laboratory number | Plantation | Location | Mean annual rainfall | Color[1] | Depth of sample | Exchangeable Bases | | | | | Total bases | | | Proportion of total bases in exchangeable form | | | Base-exchange capacity | | | | Base saturation | pH | Ultimate pH | Organic matter | Nitrogen | C/N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Calcium | Magnesium | Potassium | Manganese[2] | Total[3] | Calcium (CaO) | Magnesium (MgO) | Manganese (MnO) | Calcium | Magnesium | Manganese | Entire soil | Mineral fraction | Organic matter | Proportion of total due to organic matter | | | | | | |
| | | | Inches | | Inches | m.e./100 gm. | m.e./100 gm. | m.e./100 gm. | m.e./100 gm. | m.e./100 gm. | Percent | Percent | Percent | Percent | Percent | Percent | m.e./100 gm. | m.e./100 gm. | m.e./100 gm. | Percent | Percent | | | Percent | Percent | |
| 40–421a | Paauhau Sugar Plantation Company | Hamakua Coast, Hawaii | 90 | dk-y-br | 0–8 | 8.63 | 2.59 | 0.84 | | 12.06 | 0.54 | 0.79 | 0.44 | 45 | 6.6 | | 59.7 | 23.9 | 253 | 66.2 | 20.2 | 5.5 | 4.3 | 15.6 | 0.83 | 10.9 |
| b | | | | dk-y-br | 8–20 | 6.70 | 1.96 | .41 | | 9.07 | .39 | .79 | .29 | 48 | 5.0 | | 33.3 | 22.3 | 133 | 39.6 | 27.2 | 6.1 | 5.1 | 9.9 | .52 | 11.0 |
| 40–420a | Paauhau Sugar Plantation Company | Hamakua Coast, Hawaii | 65 | dk-y-br | 0–8 | 9.70 | 4.57 | 1.35 | 0.022 | 15.62 | .48 | 1.11 | .34 | 57 | 8.2 | 0.23 | 47.1 | 26.9 | 219 | 48.8 | 33.2 | 5.7 | 4.3 | 10.5 | .54 | 11.2 |
| b | | | | dk-y-br | 8–17 | 7.66 | 3.57 | .40 | | 11.63 | .30 | .74 | .18 | 72 | 10 | | 30.7 | 18.5 | 169 | 44.6 | 37.9 | 6.1 | 5.2 | 8.1 | .41 | 11.4 |
| 40–423a | Hamakua Mill Company | Hamakua Coast, Hawaii | 120 | dk-y-br | 0–6 | 3.62 | .87 | .73 | | 5.22 | .39 | .85 | .18 | 26 | 2.0 | | 45.6 | 14.4 | 195 | 74.0 | 11.5 | 5.5 | 4.5 | 17.3 | .66 | 15.1 |
| b | | | | dk-y-br | 6–18 | 1.20 | .21 | .66 | | 2.07 | .17 | .73 | .14 | 20 | .58 | | 38.6 | 11.3 | 242 | 74.1 | 5.4 | 5.6 | 4.8 | 11.8 | .42 | 16.3 |
| 40–422a | Hamakua Mill Company | Hamakua Coast, Hawaii | 95 | dk-y-br | 0–8 | 7.33 | 2.04 | .81 | | 10.18 | .53 | .87 | .26 | 39 | 4.7 | | 52.3 | 28.3 | 172 | 54.8 | 19.3 | 5.5 | 4.5 | 16.7 | .76 | 12.8 |
| b | | | | dk-y-br | 8–20 | 6.20 | 1.54 | .36 | | 8.10 | .40 | .84 | .25 | 43 | 3.7 | | 35.9 | 18.6 | 192 | 53.5 | 22.5 | 6.0 | 5.1 | 10.0 | .45 | 12.8 |
| 40–424a | Kaiwiki Sugar Company, Ltd. | Hamakua Coast, Hawaii | 115 | mod-br | 0–10 | 1.40 | .62 | .50 | .017 | 2.52 | .19 | .94 | .13 | 21 | 1.3 | .46 | 44.6 | 19.0 | 232 | 62.6 | 5.7 | 4.5 | 4.0 | 12.0 | .45 | 15.5 |
| b | | | | dk-y-br | 10–22 | .33 | .22 | .35 | tr | .90 | .090 | .76 | .12 | 10 | .58 | tr | 37.4 | 13.6 | 205 | 68.3 | 2.4 | 5.0 | 5.0 | 12.4 | .38 | 18.9 |
| 40–425a | Kaiwiki Sugar Company, Ltd. | Hamakua Coast, Hawaii | 115 | dk-y-br | 0–10 | 6.80 | 1.95 | .55 | .029 | 9.30 | .51 | .95 | .17 | 37 | 4.1 | .60 | 48.1 | 19.7 | 202 | 65.6 | 19.3 | 5.4 | 4.2 | 15.7 | .62 | 14.6 |
| b | | | | mod-y-br | 10–22 | 1.56 | .48 | .49 | tr | 2.53 | .10 | .77 | .17 | 44 | 1.2 | tr | 12.7 | 6.6 | 108 | 51.2 | 19.9 | 5.6 | 5.0 | 6.0 | .23 | 15.2 |
| 40–428a | Laupahoehoe Sugar Company | Hilo Coast, Hawaii | 150 | dk-y-br | 0–4 | 2.55 | .78 | .65 | .018 | 3.98 | .20 | .70 | .13 | 36 | 2.2 | .48 | 33.2 | 10.1 | 135 | 75.0 | 12.0 | 5.3 | 4.2 | 18.5 | .60 | 17.8 |
| b | | | | dk-y-br | 4–16 | .67 | .29 | .57 | tr | 1.53 | .050 | .75 | .18 | 38 | .77 | tr | 15.6 | 10.1 | 74 | 40.3 | 9.8 | 5.6 | 5.4 | 8.5 | .20 | 24.5 |
| 40–426a | Laupahoehoe Sugar Company | Hilo Coast, Hawaii | 130 | mod-y-br | 0–6 | 1.60 | .79 | .52 | .027 | 2.91 | .16 | .75 | .087 | 28 | 2.4 | 1.1 | 43.4 | 15.4 | 200 | 69.8 | 6.7 | 5.0 | 4.3 | 15.1 | .57 | 15.4 |
| b | | | | dk-y-br | 6–18 | .10 | .19 | .51 | tr | .80 | .064 | .89 | .20 | 4.7 | .43 | tr | 26.1 | 14.0 | 156 | 51.0 | 3.1 | 5.2 | 4.9 | 8.4 | .27 | 18.0 |
| 40–427a | Laupahoehoe Sugar Company | Hilo Coast, Hawaii | 130 | mod-y-br | 0–10 | 7.35 | 1.50 | .48 | .009 | 9.33 | .43 | .84 | .14 | 48 | 3.6 | .23 | 38.3 | 18.5 | 180 | 57.4 | 24.4 | 5.4 | 4.2 | 12.2 | .49 | 14.4 |
| b | | | | dk-y-br | 10–22 | 2.25 | .56 | .46 | tr | 3.27 | .16 | .67 | .14 | 39 | 1.7 | tr | 19.7 | 15.9 | 58 | 26.8 | 16.6 | 5.6 | 5.4 | 9.2 | .30 | 17.7 |
| 40–429a | Hakalau Plantation Company | Hilo Coast, Hawaii | 155 | mod-y-br | 0–8 | .89 | .53 | .32 | .022 | 1.74 | .15 | .60 | .085 | 17 | 1.8 | .85 | 37.3 | 14.0 | 156 | 68.7 | 4.7 | 4.7 | 4.1 | 16.4 | .56 | 17.0 |
| b | | | | dk-y-br | 8–20 | .14 | .22 | .31 | tr | .67 | .067 | .55 | .065 | 5.6 | .80 | tr | 29.7 | 13.1 | 198 | 59.9 | 2.3 | 4.7 | 4.5 | 9.0 | .30 | 17.5 |
| 40–430a | Honomu Sugar Company | Hilo Coast, Hawaii | 230 | dk-y-br | 0–10 | .30 | .47 | .49 | .007 | 1.26 | .17 | .90 | .088 | 4.6 | 1.0 | .27 | 32.8 | 11.0 | 142 | 71.7 | 3.8 | 5.2 | 4.7 | 15.6 | .45 | 20.0 |
| b | | | | dk-y-br | 10–22 | .030 | .19 | .56 | tr | .78 | .063 | 1.22 | .095 | 1.4 | .31 | tr | 16.8 | 11.0 | 82 | 39.9 | 4.6 | 5.3 | 4.9 | 8.2 | .18 | 26.3 |
| 40–431a | Honomu Sugar Company | Hilo Coast, Hawaii | 155 | mod-y-br | 0–8 | 2.05 | .70 | .57 | .033 | 3.32 | .24 | .73 | .12 | 24 | 1.9 | 1.0 | 35.4 | 10.2 | 171 | 75.7 | 9.4 | 5.3 | 4.7 | 15.7 | .57 | 16.0 |
| b | | | | dk-y-br | 8–20 | .69 | .30 | .70 | tr | 1.69 | .12 | .72 | .18 | 16 | .83 | tr | 19.0 | 6.4 | 156 | 69.0 | 8.9 | 5.6 | 5.2 | 8.4 | .23 | 21.1 |
| 40–432a | Pepeekeo Sugar Company | Hilo Coast, Hawaii | 230 | dk-y-br | 0–10 | .60 | .51 | .44 | .013 | 1.55 | .15 | .82 | .11 | 11 | 1.2 | .41 | 38.9 | 5.1 | 219 | 89.0 | 4.0 | 5.1 | 4.7 | 15.8 | .52 | 17.6 |
| b | | | | dk-y-br | 10–22 | .36 | .63 | .65 | tr | 1.64 | .10 | 1.09 | .11 | 10 | 1.2 | tr | 25.8 | 4.3 | 180 | 87.2 | 6.4 | 5.5 | 5.0 | 12.5 | .35 | 20.8 |
| 40–433a | Pepeekeo Sugar Company | Hilo Coast, Hawaii | 155 | mod-y-br | 0–6 | 6.38 | 2.09 | .50 | .013 | 8.97 | .62 | .84 | .074 | 29 | 5.0 | .65 | 45.4 | 13.7 | 186 | 75.3 | 19.7 | 5.8 | 4.4 | 18.4 | .69 | 15.4 |
| b | | | | dk-y-br | 6–18 | .99 | .51 | .52 | tr | 2.02 | .13 | .64 | .086 | 21 | 1.6 | tr | 25.3 | 14.6 | 116 | 48.2 | 8.0 | 5.5 | 5.1 | 10.5 | .33 | 18.4 |
| 40–434a | Pepeekeo Sugar Company | Hilo Coast, Hawaii | 130 | mod-y-br | 0–9 | 11.40 | 1.48 | .45 | .015 | 13.33 | .67 | .68 | .10 | 48 | 4.4 | .53 | 43.4 | 9.0 | 223 | 82.7 | 30.7 | 5.9 | 4.4 | 16.1 | .66 | 14.6 |
| b | | | | dk-y-br | 9–21 | 3.63 | .42 | .55 | tr | 4.60 | .23 | .64 | .11 | 44 | 1.3 | tr | 18.0 | 7.6 | 129 | 61.7 | 25.6 | 6.2 | 5.4 | 8.6 | .30 | 16.6 |
| 40–435a | Onomea Sugar Company, Ltd. | Hilo Coast, Hawaii | 175 | mod-y-br | 0–10 | 2.76 | 1.16 | .27 | .026 | 4.19 | .38 | 1.12 | .14 | 20 | 2.1 | .65 | 40.9 | 12.0 | 230 | 74.2 | 10.2 | 5.2 | 4.5 | 13.2 | .56 | 13.6 |
| b | | | | mod-y-br | 10–22 | .91 | .49 | .37 | tr | 1.77 | .14 | 2.41 | .25 | 18 | .41 | tr | 27.0 | 5.8 | 323 | 80.0 | 6.6 | 5.7 | 5.4 | 7.0 | .24 | 16.8 |
| 40–440 | Hawaiian Sugar Planters' Association Substation (Hilo) | Hilo Coast, Hawaii | 165 | mod-y-br | 0–8 | 8.55 | 2.60 | .57 | .031 | 11.72 | .73 | 1.71 | .16 | 33 | 3.0 | .68 | 47.4 | 13.1 | 234 | 76.5 | 24.8 | 5.6 | 4.3 | 15.5 | .62 | 14.5 |
| 41–161a | Hilo Sugar Company (Kaiwiki) | Hilo Coast, Hawaii | 215 | mod-y-br | 0–6 | .20 | .28 | .11 | tr | .59 | .18 | 1.05 | .10 | 3.1 | .53 | tr | | | | | | 5.0 | | 16.0 | .56 | 16.5 |
| b | | | | dk-y-br | 6–18 | .086 | .26 | .12 | tr | .47 | .076 | 1.03 | .16 | 3.2 | .50 | tr | | | | | | 5.4 | | 9.9 | .32 | 18.0 |
| 41–162a | Hilo Sugar Company (Amauulu) | Hilo Coast, Hawaii | 190 | mod-y-br | 0–6 | 3.14 | 1.12 | .20 | .012 | 4.46 | .68 | 2.41 | .081 | 13 | .93 | .53 | | | | | | 5.1 | | 17.7 | .66 | 15.6 |
| b | | | | mod-y-br | 6–18 | .67 | .42 | .029 | tr | 1.12 | .16 | 3.43 | .13 | 12 | .25 | tr | | | | | | 5.7 | | 10.0 | .32 | 18.1 |
| 41–163 | Hilo Sugar Company (Kaumana) | Hilo Coast, Hawaii | 185 | mod-y-br | 0–12 | 1.10 | .44 | .24 | .012 | 1.78 | .56 | 1.89 | .084 | 5.5 | .47 | .53 | | | | | | 5.1 | | 17.0 | .59 | 16.7 |
| 40–439 | Waiakea Mill Company | South Hilo, Hawaii | 180 | wk-br | 0–12 | 4.88 | 2.25 | .43 | .058 | 7.56 | 2.24 | 3.72 | .19 | 6.1 | 1.2 | 1.1 | 57.8 | 13.4 | 182 | 82.8 | 13.1 | 5.4 | 4.4 | 26.3 | .91 | 16.7 |
| 40–436a | Olaa Sugar Company, Ltd. | Puna, Hawaii | 190 | wk-br | 0–10 | 2.30 | 1.19 | .46 | .054 | 3.95 | 3.14 | 3.65 | .14 | 2.1 | .65 | 1.4 | 58.7 | 9.1 | 198 | 88.5 | 6.7 | 5.2 | 4.5 | 26.7 | 1.02 | 15.2 |
| b | | | | wk-br | 10–22 | .71 | .50 | .55 | .022 | 1.76 | 2.35 | 3.50 | .13 | .85 | .29 | .59 | 44.9 | 8.2 | 225 | 84.8 | 3.9 | 5.5 | 5.3 | 16.9 | .70 | 14.0 |
| 40–437a | Olaa Sugar Company, Ltd. | Puna, Hawaii | 170 | dk-y-br | 0–8 | 3.25 | 1.87 | .41 | .052 | 5.53 | 3.24 | 9.00 | .036 | 2.8 | .42 | 4.6 | 44.7 | 11.1 | 174 | 81.8 | 12.4 | 5.4 | 4.5 | 22.3 | .90 | 14.3 |
| b | | | | dk-y-br | 8–20 | .99 | .60 | .37 | .012 | 1.96 | 2.78 | 9.90 | .10 | 1.0 | .12 | .42 | 32.1 | 13.4 | 140 | 64.5 | 6.1 | 5.8 | 5.1 | 14.8 | .52 | 16.5 |
| 40–438 | Olaa Sugar Company, Ltd. | Puna, Hawaii | 140 | wk-br | 0–12 | 10.05 | 3.73 | .68 | .052 | 14.46 | 3.20 | 7.05 | .13 | 8.8 | 1.1 | 1.4 | 49.6 | 13.4 | 138 | 80.8 | 29.2 | 5.6 | 4.3 | 26.1 | .95 | 16.0 |
| 40–441a | Kilauea Sugar Plantation Company | Kilauea, Kauai | 100 | mod-y-br | 0–8 | 13.50 | 3.32 | .18 | .011 | 17.00 | .70 | .63 | .090 | 53 | 11 | .43 | 25.7 | 2.6 | 215 | 90.7 | 66.1 | 6.0 | 3.6 | 10.8 | .33 | 18.9 |
| b | | | | mod-y-br | 8–20 | 1.85 | 1.15 | .071 | tr | 3.07 | .16 | .50 | .10 | 32 | 4.6 | tr | 10.6 | .61 | 323 | 94.2 | 29.0 | 5.8 | 4.5 | 3.1 | .069 | 25.6 |
| 40–442a | Kilauea Sugar Plantation Company | Kilauea, Kauai | 65 | lt-y-br | 0–8 | 4.40 | 1.80 | .19 | .065 | 6.39 | .27 | 1.06 | .14 | 46 | 3.4 | 1.6 | 20.7 | 4.7 | 247 | 78.7 | 30.8 | 5.4 | 3.7 | 6.6 | .29 | 13.1 |
| b | | | | mod-y-br | 8–20 | 1.49 | .55 | .073 | tr | 2.11 | .15 | 1.01 | .10 | 28 | 1.1 | tr | 7.8 | 2.4 | 229 | 70.5 | 27.0 | 6.0 | 5.3 | 2.4 | .12 | 11.3 |
| 40–443a | The Lihue Plantation Company, Ltd. | Lihue, Kauai | 80 | mod-y-br | 0–12 | 1.87 | .52 | | tr | | .23 | .57 | .05 | 23 | 1.8 | tr | | | | | | 5.0 | | 8.0 | .23 | 20.3 |
| b | | | | mod-y-br | 12–24 | 1.57 | .29 | | tr | | .22 | .56 | .08 | 20 | 1.0 | tr | | | | | | 5.1 | | 4.5 | .11 | 24.6 |
| 40–444 | Honolulu Plantation Company | Aiea, Oahu | 40 | mod-br | 0–10 | 8.38 | 4.82 | 1.06 | .16 | 14.26 | .44 | .63 | .37 | 53 | 15 | 1.5 | 14.8 | 11.3 | 77 | 27.0 | 96.2 | 6.4 | 4.3 | 5.2 | .32 | 9.4 |
| 40–217 | Ewa Plantation Company | Ewa, Oahu | 25 | mod-br | 0–10 | 7.47 | | 1.00 | .10 | | .44 | 1.35 | .28 | 48 | | 1.3 | 14.1 | 11.2 | 148 | 22.0 | | 6.5 | 3.8 | 2.1 | .11 | 11.0 |
| 40–395 | Hawaii Agricultural Experiment Station | Honolulu, Oahu | 35 | wk-br | 0–10 | 18.60 | 10.50 | .80 | .032 | 29.90 | 2.79 | 8.38 | .40 | 19 | 2.5 | .28 | 41.8 | | | | 71.2 | 6.6 | 4.2 | 6.1 | .28 | 12.6 |
| 41–156a | Hawaii Agricultural Experiment Station Substation | Poamoho, Oahu | 45 | mod-br | 0–12 | 5.92 | | .17 | | | | | | | | | | | | | | 5.6 | | | | |
| b | | | | mod-br | 12–24 | 5.62 | | .15 | | | | | | | | | | | | | | 6.0 | | | | |
| 40–288 | Hawaiian Sugar Planters' Association Experiment Station | Honolulu, Oahu | 30 | mod-y-br | 0–12 | 26.20 | 10.00 | | | | 2.34 | 4.87 | .43 | 31 | 4.1 | | 36.3 | 32.6 | 137 | 13.2 | | 7.0 | 4.3 | 3.5 | .14 | 14.5 |

[1] U.S.D.A. soil colors (49): br = brown y = yellowish lt = light dk = dark wk = weak mod = moderate

[2] tr $\neq$ .005 m.e./100 gm.

[3] Calcium, magnesium, and potassium.

TABLE 2. Chemical properties of humid-region virgin and agricultural soils

| Laboratory number | Plantation | Mean annual rainfall | Color[1] | Vegetation | Depth of sample | Exchangeable bases: Calcium | Exchangeable bases: Magnesium | Exchangeable bases: Potassium | Exchangeable bases: Manganese[2] | Exchangeable bases: Total[3] | Total bases: Calcium (CaO) | Total bases: Magnesium (MgO) | Total bases: Manganese (MnO) | Proportion of total bases in exchangeable form: Calcium | Proportion of total bases in exchangeable form: Magnesium | Proportion of total bases in exchangeable form: Manganese | pH | Organic matter | Nitrogen | C/N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Inches* | | | *Inches* | *m.e./100 gm.* | *m.e./100 gm.* | *m.e./100 gm.* | *m.e./100 gm.* | *m.e./100 gm.* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | | *Percent* | *Percent* | |
| 40–423a | Hamakua Mill Company | 120 | dk-y-br | Sugarcane | 0–6 | 3.62 | 0.87 | 0.73 | | 5.22 | 0.39 | 0.85 | 0.18 | 26 | 2.0 | | 5.5 | 17.3 | 0.66 | 15.1 |
| b | | | dk-y-br | | 6–18 | 1.20 | .21 | .66 | | 2.07 | .17 | .73 | .14 | 20 | .58 | | 5.6 | 11.8 | .42 | 16.3 |
| 41–164a | Hamakua Mill Company | 120 | wk-br | Forest | 0–6 | 5.08 | 2.61 | .43 | 0.035 | 8.12 | .41 | .71 | .16 | 35 | 7.3 | 0.77 | 4.7 | 25.9 | 1.02 | 14.7 |
| b | | | wk-br | (virgin) | 6–18 | .57 | .47 | .10 | .009 | 1.14 | .17 | .66 | .13 | 9.3 | 1.4 | .24 | 4.9 | 20.2 | .75 | 15.6 |
| 40–430a | Honomu Sugar Company | 230 | dk-y-br | Sugarcane | 0–10 | .30 | .47 | .49 | .007 | 1.26 | .17 | .90 | .088 | 4.6 | 1.0 | .27 | 5.2 | 15.6 | .45 | 20.0 |
| b | | | dk-y-br | | 10–22 | .030 | .19 | .56 | tr | .78 | .063 | 1.22 | .095 | 1.4 | .31 | tr | 5.3 | 8.2 | .18 | 26.3 |
| 41–165a | Honomu Sugar Company | 230 | wk-br | Forest | 0–9 | .84 | 1.82 | .44 | .018 | 3.10 | .13 | .55 | .036 | 18 | 6.6 | 1.6 | 4.6 | 29.8 | 1.09 | 15.9 |
| b | | | dk-br | (virgin) | 9–21 | .21 | .38 | .14 | tr | .73 | .046 | .65 | .030 | 12 | 1.2 | tr | 4.9 | 15.2 | .48 | 18.4 |
| 40–432a | Pepeekeo Sugar Company | 230 | dk-y-br | Sugarcane | 0–10 | .60 | .51 | .44 | .013 | 1.55 | .15 | .82 | .11 | 11 | 1.2 | .41 | 5.1 | 15.8 | .52 | 17.6 |
| b | | | dk-y-br | | 10–22 | .36 | .63 | .65 | tr | 1.64 | .10 | 1.09 | .11 | 10 | 1.2 | tr | 5.5 | 12.5 | .35 | 20.8 |
| 41–166a | Pepeekeo Sugar Company | 230 | dk-y-br | Broken forest | 0–9 | .47 | .92 | .22 | .012 | 1.61 | .16 | .65 | .042 | 8.2 | 2.8 | 1.1 | 5.0 | 21.7 | .67 | 18.8 |
| b | | | dk-y-br | (virgin) | 9–21 | .27 | .72 | .072 | .005 | 1.07 | .066 | 1.18 | .072 | 11 | 1.2 | .24 | 5.3 | 13.6 | .40 | 19.7 |
| 41–161a | Hilo Sugar Company | 215 | mod-y-br | Sugarcane | 0–6 | .20 | .28 | .11 | tr | .59 | .18 | 1.05 | .10 | 3.1 | .53 | tr | 5.0 | 16.0 | .56 | 16.5 |
| b | | | dk-y-br | | 6–18 | .086 | .26 | .12 | tr | .47 | .076 | 1.03 | .16 | 3.2 | .50 | tr | 5.4 | 9.9 | .32 | 18.0 |
| 41–167a | Hilo Sugar Company | 215 | mod-y-br | Broken forest | 0–6 | .38 | .36 | .13 | tr | .87 | .31 | .62 | .028 | 3.4 | 1.2 | tr | 4.8 | 17.9 | .54 | 19.2 |
| b | | | dk-y-br | (virgin) | 6–18 | .079 | .25 | .031 | tr | .37 | .11 | 1.95 | .062 | 2.0 | .26 | tr | 5.2 | 12.5 | .37 | 19.5 |
| 41–162a | Hilo Sugar Company | 190 | mod-y-br | Sugarcane | 0–6 | 3.14 | 1.12 | .20 | .012 | 4.46 | .68 | 2.41 | .081 | 13 | .93 | .53 | 5.1 | 17.7 | .66 | 15.6 |
| b | | | mod-y-br | | 6–18 | .67 | .42 | .029 | tr | 1.12 | .16 | 3.43 | .13 | 12 | .25 | tr | 5.7 | 10.0 | .32 | 18.1 |
| 41–168a | Hilo Sugar Company | 190 | dk-y-br | Grass and fern | 0–6 | .77 | 1.62 | .10 | .012 | 2.49 | .26 | .65 | .037 | 8.3 | 5.0 | 1.1 | 5.0 | 14.4 | .47 | 17.8 |
| b | | | mod-y-br | (virgin) | 6–18 | .031 | .20 | .054 | tr | .29 | .33 | 5.35 | .11 | .26 | .075 | tr | 5.2 | 9.8 | .29 | 19.5 |

[1] U.S.D.A. soil colors (49): br = brown y = yellowish lt = light dk = dark wk = weak mod = moderate [2] tr $\neq$ .005 m.e./100 gm. [3] Calcium, magnesium, and potassium.

TABLE 3. Influence of organic matter on the ultimate pH of the soil

| Laboratory number | Plantation | Depth of sample | Organic matter in untreated soil | Treatment | Ultimate pH: Entire soil | Ultimate pH: Mineral fraction | Ultimate pH: Increase |
|---|---|---|---|---|---|---|---|
| | | *Inches* | *Percent* | | | | |
| 40–441b | Kilauea Sugar Plantation Company | 8–20 | 3.1 | $H_2O_2$ | 4.5 | 5.1 | 0.6 |
| 40–288 | Hawaiian Sugar Planters' Association Experiment Station, Honolulu | 0–12 | 3.5 | Ignition | 4.3 | 4.6 | .3 |
| 40–435b | Onomea Sugar Company, Ltd. | 10–22 | 7.0 | Ignition | 5.4 | 6.3 | .9 |
| 40–441a | Kilauea Sugar Plantation Company | 0–8 | 10.8 | $H_2O_2$ | 3.6 | 4.7 | 1.1 |
| 40–435a | Onomea Sugar Company, Ltd. | 0–10 | 13.2 | Ignition | 4.5 | 6.1 | 1.6 |
| 40–440 | Hawaiian Sugar Planters' Association Substation, Hilo | 0–8 | 15.5 | Ignition | 4.3 | 6.2 | 1.9 |